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LIQUID AEROBIC COMPOSTING OF CATTLE WASTES AND EVALUATION OF BY-PRODUCTS

Frank Grant, et al

Chino Basin Municipal Water District

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16. Abstract
~~The study was undertaken to determine~~ the technical and economic feasibility was determined of treating dairy waste in a liquid state by a tandem thermophilic-mesophilic aerobic stabilization process, more commonly described as liquid composting. Experimental apparatus were set up at an operating dairy, ~~and a program was organized to study the process. The study showed that~~ a large fraction of dairy manure is relatively resistant to rapid biological degradation even at thermophilic temperatures. Antithetical requirements of sufficient oxygen for maximum biological activity and minimum air flow to preclude the need for an external heat source could not be satisfied with the particular experimental apparatus when utilizing air as the oxygen source. Improved results were obtained with an oxygen-enriched air supply which pointed out the potential advantage of a pure oxygen system. Preliminary cost estimates for a liquid composting process to serve 500 cows were developed within the context of current dairy operation economics. ~~The estimates showed that~~ the process is considerably more costly than current, conventional, composting operations. ~~and that~~ the cost of the process is substantially above levels which could be maintained by dairy operations. (EPA)

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Project No. S801647
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ABSTRACT

The Santa Ana River basin of California has a total dairy cow population of approximately 174,000. Most of these cows are confined to a relatively small portion of the basin in the vicinity of Chino and Corona. The wastes from these cows burden the basin groundwater resources, and the Santa Ana Regional Water Quality Control Board has issued waste discharge requirements for the dairies.

The current study was undertaken to determine the technical and economic feasibility of treating dairy waste in a liquid state by a tandem thermophilic-mesophilic aerobic stabilization process, more commonly described as liquid composting. It was envisioned that thermophilic temperatures would speed the stabilization process, biological heat generation would maintain desired temperatures, and the product would be free of pathogens and weed seeds because of the elevated operating temperatures. A well stabilized product would also be free of odors and attractiveness for flies.

Experimental apparatus were set up at an operating dairy and a program was organized to study the process. The study showed that a large fraction of dairy manure is relatively resistant to rapid biological degradation even at thermophilic temperatures. Antithetical requirements of sufficient oxygen for maximum biological activity and minimum air flow to preclude the need for an external heat source could not be satisfied with the particular experimental apparatus when utilizing air as the oxygen source. Improved results were obtained with an oxygen-enriched air supply which pointed out the potential advantage of a pure oxygen system.

It is suggested that future investigations focus upon the use of pure oxygen as the oxygen source for the process and upon mechanical aeration equipment as opposed to diffused aeration equipment to supply the oxygen. This work would confirm the technical feasibility of the process. Preliminary cost estimates for a liquid composting process to serve 500 cows were developed within the context of current dairy operation economics. The estimates showed that the process is considerably more costly than current, conventional, composting operations and that the cost of the process is substantially above levels which could be maintained by dairy operations.

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Through April, 1973, the research program was directed by Dr. G.N. Tyson, Jr. who with the assistance of Dr. Robert Austin and Mr. Francis Brommenschenkel assembled the equipment, established sampling and analytical procedures, and conducted the first phases of experimentation. Dr. Maurice Lynch monitored administrative details. From May, 1973, Mrs. Marilyn Thompson served as project director with Dr. Frank Grant assigned responsibility for all project details. Mr. Francis Brommenschenkel served as principal operator of the experimental apparatus and assisted Mrs. Thompson and Dr. Grant in administrative and technical matters. Several other employees of Chino Basin Municipal Water District provided support in preparing the study site, operating the experimental apparatus, analyzing samples, and performing administrative details.

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SECTION I

CONCLUSIONS

Principal conclusions of this study within the constraints of the equipment and aeration methods are:

1. The digestibility of dairy cattle manure appears to be limited even at thermophilic temperatures. A portion of the organics is readily digestible but the majority of the organic material degrades rather slowly even at thermophilic temperatures.

2. A pasteurized product free of odors and probably free of pathogens and weed seeds can be produced utilizing procedures of this study. However, the product retains a large percentage of biodegradable material but is appropriate for land spreading as a soil conditioner with fertilizer and moisture retention values if properly isolated from surface waters. The total fixed dissolved solids of the product are probably unaffected by the process and therefore the dissolved solids would remain a potential burden upon groundwater supplies.

3. Utilizing air as the oxygen source, insufficient heat is generated biologically to compensate for energy losses and maintain the thermophilic temperatures. A large energy input from mixing or some other source is needed to maintain thermophilic temperatures.

4. The necessary substrate-organisms-oxygen contact to produce rapid stabilization of organic material appears to be limited by the amount of oxygen that can be transferred from the air supply. Conventional equipment appears to be inadequate at thermophilic temperatures and high solids content to transfer the oxygen needed to maintain a high rate of biological activity.

5. Results with an oxygen-enriched air supply indicate that greater biological activity and reduced energy losses can be achieved with a pure oxygen supply.

6. The diversity of biological organisms in the treatment process appears to be diminished at elevated temperatures. This may tend to limit the range of organic material that can be stabilized at thermophilic temperatures.

7. Advantages, if any, of a liquid composting process over a conventional composting process presently appear to be more than offset by treatment limitations and costs.

8. Estimated costs of a complete treatment process appear to be too high for current dairy operations.

SECTION II

RECOMMENDATIONS

1. Further pilot-scale work to develop a liquid, thermophilic, aerobic treatment process for the dairy wastes produced in the Upper Santa Ana watershed should not be actively supported at the present time.

2. Future research to develop the process should be directed towards achieving efficient mixing and high oxygen transfer efficiencies such as may be obtained with a pure oxygen treatment system.

SECTION III

INTRODUCTION

GENERAL

Urbanization and suburbanization of rural lands have reduced the amount of land available for animal waste spreading. Total animal populations have increased with increased demands for meat, poultry and animal products. Rising real estate costs and favorable economics of mechanized feeding, milking, etc., have spurred trends towards large animal populations on small acreage. In many cases, therefore, a situation exists where profuse quantities of animal manure are produced with insufficient land for direct land disposal.

High density animal confinement is exemplified by dairies in the Chino-Corona area of the upper Santa Ana River basin of California. Table 1 summarizes the dairy situation in the upper basin. Specifically the table shows a total of approximately 174,000 cows in the upper basin with approximately 126,000 cows confined within the area around Chino and Corona. This concentrated dairy area consists of approximately 9,300 hectares (36 sq mi).* A dairy cow is equivalent to approximately 25 people in terms of suspended solids production. This indicates that 174,000 cows are equivalent to a human population of several million, and in the Chino-Corona area the cow density is equivalent to several times the human population density of such high density cities as New York.

A typical 8 hectare (20 acre) dairy in this area may have 400 cows. One third of the 8 hectares may be used for the dairy home, milking parlor and feeding pens, with the remaining two-thirds devoted to cropland and spray irrigation of washwater from the milking parlor. The manure produced in the feeding pens is collected and removed periodically to the cropland, neighboring farms, composting operations, and literally any other place to which the dairyman has access. Wastes often accumulate and erode, contaminating water supplies.

The contamination of water resources by animal wastes has been adequately documented in numerous publications.[1-11] In recognition of this, the California Regional Water Quality Control Board, Santa Ana Region, has issued what has been termed Phase I and Phase II requirements for the dairies in the Santa Ana watershed. The substance of these requirements is as follows:

1. There shall be no discharge of dairy wastes to lands not owned or controlled by the discharger, nor to lands for which the discharger has not obtained permission for waste disposal from the land owner.

2. The discharger shall provide facilities to contain the runoff from manured areas that would result from 1.3 times the 10-year 24-hour rainfall. (This corresponds to approximately 1.3 x 11.55=15 cm (5.9 in. of water.)

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*The modern metric system of units and symbols is employed throughout this report followed by customary units and symbols in parenthesis.

Table 1. SUMMARY OF DAIRY POPULATION AND WASTE PRODUCTION IN UPPER SANTA ANA RIVER BASIN

	County		Area totals
	San Bernardino	Riverside	
Number of dairies	292 (203)[a]	142 (102)	434 (305)
Milking cows	88,300	44,800	133,100
Dry cows	21,300	11,700	33,000
Total number of equivalent cows[b]	114,500 (75,600)	59,200 (50,400)	173,700 (126,000)
Average number of equivalent cows per dairy	392	417	400
Gross dairy area (ha)	3,610	2,340	5,950
Disposal area (ha)	2,550	2,210	4,760
Cows per hectare of gross dairy area	31.7	25.3	29.2
Cows per hectare of disposal area	44.9	26.8	36.5
Dairy wash water (l/sec)	170 (110)	90 (70)	260 (180)
Daily solids production (t)	570 (375)	290 (250)	860 (625)

[a]The numbers in parentheses pertain to the dairies concentrated in the Chino-Corona area

[b]"Equivalent" is computed by counting heifers as 1/2 cow and calves as 1/5 cow with respect to the waste production of a mature milk cow.

Source of data is California RWQCB, Santa Ana Region.

3. The discharge of manure waste to lands owned or controlled by the discharger shall not exceed 3 tons (dry weight) per acre (6.7 metric tons per hectare) per year. This is equivalent to 1.5 times the amount of manure produced by one cow in one year.

4. Neither the treatment nor the discharge of dairy wastes shall cause a nuisance.

5. The discharge of dairy wastes shall not alter the quality of waters of the state to a degree which unreasonably affects such waters for beneficial uses, or affects facilities which serve such beneficial uses.

The schedule for compliance includes completion of facilities to meet requirement 2 by October 1, 1973 (Phase I), and requirement 3 by March 1, 1974 (Phase II). Representatives of the dairymen have asked the courts to compel a reconsideration of Phase I order and to issue a stay order to prevent the Regional Board from enforcing Phase I. The request for stay order was refused and representatives of the dairymen are now (October, 1973) working with the Regional Board to work out steps for the dairy industry to achieve compliance with the orders.

A substantial volume of manure needs to be removed from the Santa Ana River Basin to meet the Regional Board requirements. Based on the assumption that a cow produces an equivalent of 14 liters (0.5 cu ft) of composted manure per day (this takes into account a volume reduction from raw to composted manure), the total amount of composted manure generated is approximately 900,000 cubic meters (32 million cu ft) per year. Ten percent of this can be spread on dairy disposal land. Additional cropland exists within the upper Santa Ana River basin and if this land were to accept manure at the rate of 6.7 metric tons per hectare (or 1.5 cows per acre), at least 15 percent more manure could be disposed of. However, a major portion would remain to be exported from the upper Santa Ana River basin or isolated from basin water supplies. A survey of current composting operations indicates that the amount of manure currently removed from dairies for composting is equivalent to approximately 300,000 cubic meters (11 million cu ft) per year as compost. The compost supplies home gardeners, landscaping firms and commercial farmers. A portion of the compost is spread upon the available cropland within the basin, but the majority of it is exported. In any case the data indicate a need to develop additional manure treatment and/or disposal activities in order to export or isolate as much as one half the total manure production.

In addition to considerations of water quality degradation, the disposal of manure creates a potential for production of particulate matter, ammonia, flies and malodors. Particulate matter affects health, irritates eyes, causes soiling and reduces visibility.[12] Ammonia can be toxic, can discolor fabric dyes, and may be absorbed in bodies of water, thereby increasing nitrogen concentrations and potential for growth of undesirable aquatic organisms. Flies and malodors are unquestionably the greatest complaint of residents living in neighborhoods around dairies.[13] Flies cause a nuisance and carry filth which may contain pathogenic organisms. Flies have been implicated in spreading diseases to both humans and animals. Malodors produce mental and physiological effects such as nausea, headache, loss of sleep, loss of appetite, curtailment of water intake and allergic reactions.[14] Malodors also decrease personal and community pride, reduce capital improvement and investment in a community, drive higher socio-economic classes from a community, and reduce tourist trade, property values, tax revenues, payrolls and sales.[14]

NEED FOR STUDY

The current project evolved from the background of increasing urbanization of agricultural lands in the southern California area and inadequate treatment and disposal methods for the Chino-Corona area in particular. Many of the dairies in this area came from former dairy areas in southern California when pressures of urbanization forced them out. In the Chino-Corona area they are again facing urbanization pressures in addition to the regulatory activities of the Regional Water Quality Control Board. Adequate treatment and disposal facilities for dairy wastes would eliminate the large majority of objectionable characteristics about dairies and thereby reduce pressures which force them out.

As stated in the proposal to EPA for this project, the need for study is twofold: (1) there is a definite, ever-increasing need for treating livestock wastes, and (2) in view of the limitation of existing treatment processes, it is evident that better treatment processes are needed. The current investigation therefore focuses upon the applicability of a specific treatment process to the stabilization of dairy cattle waste. The process is identified as a liquid, thermophilic-mesophilic, aerobic composting process.

LOCATION

The study site was adjacent to feeding pens located on the Lewis B. Aukeman Dairy, 8425 East Walnut Avenue, Ontario, California.

OBJECTIVE

The original principle objective of this project was to demonstrate the technical feasibility and economic potential of a rapid-stabilizing, minimum space-requiring approach to treating high strength cattle wastes. Specific objectives were:

1. Establish the design and operating parameters of a thermophilic and a tandem thermophilic-mesophilic aerobic stabilization process.

2. Determine detention times at thermophilic temperatures needed to achieve pathogen elimination.

3. Test the feasibility of mathematically modeling and simulating on a computer the thermophilic and thermophilic-mesophilic operations to optimize performance and facilitate extension of these processes to treatment of other livestock and high strengh wastes.

4. Show that the heat produced by microbial thermogenesis will maintain thermophilic temperatures without addition of external thermal energy.

5. Develop design data and operating requirements for a pilot plant capable of handling wastes from 500 head of cattle.

6. Perform a preliminary economic evaluation of the processes based on extrapolations of the bench scale results.

These objectives were optimistically presented in the original proposal and formed the basis for the direction of the experimental work.

SECTION IV

AEROBIC THERMOPHILIC TREATMENT PROCESS

THEORETICAL CONSIDERATIONS

A theoretical development and a literature review of thermophilic aerobic digestion have been presented by Andrews and Kambhu.[16, 17] The thermophilic temperature range is often considered to be between 49 and 60° C (120-140° F), although some researchers choose to define a wider thermophilic range, for example between 42 and 65° C (108-149° F). Certain bacteria thrive at thermophilic temperatures and in many cases produce the heat needed to maintain high temperatures such as in composting and certain industrial fermentations.

Among the potential advantages of a thermophilic aerobic process over a corresponding mesophilic (temperature range below the thermophilic range) process are: increased reaction rates leading to greater volatile solids destruction in a specified amount of time; increased fraction of organic solids that can be biologically destroyed; increased destruction of pathogenic organisms because of their inability to survive high temperatures; destruction of undesirable weed seeds; and possibly improved solids liquid separation. Such advantages have been demonstrated in other research work.[13, 18]

The basic theoretical framework utilized in the current investigation is that developed by Andrews and Kambhu. The mathematical model which they developed is based on first order reaction kinetics; the rate of oxidation of organic material is therefore represented by the equation:

$$d(BVS)/dt = -K_T (BVS) \qquad (1)$$

where (BVS) = concentration of biodegradable volatile solids
K_T = reaction rate coefficient, $days^{-1}$ at temperature T
t = time, days

A material balance for biodegradable volatile solids (BVS) in a completely-mixed, continuous-flow, steady-state reactor gives the following:

$$(BVS)_1 = (BVS)_o/(1+K_T\Theta) \qquad (2)$$

where o = subscript denoting influent
1 = subscript denoting effluent
Θ = reactor resident time, days

It is recognized that first order reaction kinetics may be a severe simplification of much more complex biochemical phenomena actually taking place during the stabilization of cattle manure. The rate of stabilization is visualized to be a function of temperature and BVS concentration. However, in addition to these two variables the true rate very likely depends upon mixing, oxygen transfer rate, limiting nutrients, the organic compounds being oxidized and the concentration and type of microorganisms. The merits of first order kinetics involve mathematical simplicity and convenience for incorporating oxygen consumption rates and generation of thermal energy into a mathematical model.

An analysis by Andrews and Kambhu of previous data showed that the ratio of oxygen utilized to organic solids oxidized ranged from 1.4 to 1.6 kg O_2/kg of volatile solids (VS) for typical waste materials in those cases where nitrogenous oxygen demand is insignificant. This ratio gives the oxygen equivalent (OE) of the BVS. The amount of heat generated in the oxidation of typical organic materials was found to range from 13,300 to 15,100 kJ/kg OE (5,700 to 6,500 Btu/lb OE) with an average of 14,200 kJ/kg OE (6,100 Btu/lb OE) when nitrogenous oxidation is insignificant. These values correspond to an organic material with a heating value of (14,200 kJ/kg OE x 1.5 kg OE/kg VS =) 21,300 kJ/kg VS (9,150 Btu/lb VS).

Estimates of the rate constant, K_T, for various substrates based on work of previous investigators range from 0.1 to 0.2 $days^{-1}$ at 20° C. At 60° C limited data show that the value increases to the range 0.25 to 0.4 $days^{-1}$, indicating that there is a 2.5 to 3-fold increase in the value of the rate constant at 60° C over 20° C.

Cattle excrement is known not to be as pustrescible as that from many other animals and human beings. The principal explanation is that cattle manure reflects cattle diet and metabolism and contains a large portion of cellulosic material and lignins which are characteristically more difficult and slower to degrade than are many other foodstuffs. Therefore the rate constant for cattle manure oxidation may be considerably lower than that for other wastes. In fact, a recent study indicates that there may be two separate K rates with the first being the oxidation of readily degradable materials and the second, the slower breakdown of other materials.[19] These slowly degradable materials may account for 75 percent of the total biodegradable materials and exert a significant oxygen demand over periods in excess of 20 days at a rate on the order of 1/20 to 1/30 that of the readily degradable materials. Recognition of this anomalous behavior can be important in interpreting results of biochemical oxygen demand (BOD) tests and in establishing the appropriate percentage of cattle manure that may be considered biodegradable. For example, the 5-day biochemical oxygen demand (BOD_5) may represent less than 20 percent of the ultimate biochemical oxygen demand (BOD_L).

An energy balance is needed to complete a mathematical model of the aerobic, thermophilic treatment process. The important energy inputs to the process are energy of mixing, biological heat production, and direct heat input from heating coils, etc. Energy losses include heat lost to the surroundings through reactor walls, latent heat of vaporization of water picked up by the air stream in passing through the reactor, sensible heat increase of the air stream, and sensible heat increase of the liquid waste stream in passing through the reactor.

The energy balance may therefore be represented by:

$$H_r = H_m + H_b - (H_l + H_v + H_g + H_s) \qquad (3)$$

where H_r = rate of sensible heat increase of the contents of the reactor, watts

H_m = rate of heat input from mixing and other direct heat input, watts

H_b = rate of heat production by biological (and chemical) oxidation of BVS, watts

H_l = rate of heat loss represented by the difference in sensible heat between the influent and effluent liquid streams, watts

H_v = rate of heat loss as latent heat in water vapor, watts
H_g = rate of heat loss represented by the difference in sensible heat between the influent and effluent air (or gas) streams, watts
H_s = rate of heat loss to the surroundings, watts

Each of these terms can be estimated from physical constants and measurements.

It is pertinent to point out some of the results of Andrews and Kambhu's model for a complete-mixing, continuous-flow reactor at steady state conditions. Some of the important assumptions input to the results are:

1. 70 percent of the total solids are volatile and of the volatile solids, 70 percent are biodegradable.

2. 1.5 kg of oxygen is utilized for each kg of volatile solids destroyed and 14,200 kJ of heat is released per kg of oxygen utilized with ammonia as a product (6,100 Btu released per lb of oxygen utilized).

3. Power input for mixing and gas transfer is constant at 26.3 W/m^3 (1.0 hp per 1,000 cu ft of reactor).

4. The outside air temperature is -6.6° C (20° F), the influent liquid temperature is 4.4° C (40° F), the effluent streams are at the same temperature as the reactor contents, the influent gas stream is dry, and the effluent gas stream is saturated with water.

5. Oxygen transfer efficiency is 15 percent and the overall heat transfer coefficient is 0.5684 J/m^2 sec ° C (0.10 Btu/sq ft/° F/hr) for a cylindrical reactor with height equal to diameter.

6. The rate constant K_T is represented by a smooth curve which has values of 0.10, 0.145, 0.21, 0.24, 0.275, 0.295, and 0.29 $days^{-1}$ at temperatures of 20°, 30°, 40°, 45°, 50°, 55° and 60° C, respectively.

The hypothetical model treats domestic wastewater sludge or mixtures of domestic wastewater sludge and ground garbage from a city with a population of 10,000. A summary of observations is as follows:

1. For a contribution of 0.09 kg (0.2 lb) of total solids per capita (630 kg/day VS) at 3 percent concentration (30 m^3/day) and 10-day hydraulic and solids residence time, the reactor operates at 39° C (102° F) which is below the thermophilic temperature range. Heat input from mixing is approximately 10 percent of the total heat input from biological activity and mixing. At the operating temperature of 39° C the heat losses are 51, 17, 7 and 6 kw for H_l, H_v, H_g and H_s respectively. The losses would remain approximately in this same proportion at higher temperatures except for the loss due to latent heat of vaporization which increases exponentially with temperature. Approximately 67 percent of the biodegradable volatile solids (or 47 percent of the total volatile solids) is destroyed.

2. A five-fold increase of mixing energy would raise the reactor temperature to 49° C (120° F). Approximately 73 percent of the biodegradable volatile solids would be destroyed at the 10-day residence time.

3. Increasing the amount of total solids to give a concentration of 4.5 percent (no change in volumetric flow) would raise the reactor operating temperature to 46° C (115° F). Approximately 71 percent of the biodegradable volatile solids would be destroyed at the 10-day residence time.

4. Increasing the residence time to 15 days would result in approximately 75 percent destruction of biodegradable volatile solids (or approximately 53 percent destruction of total volatile solids).

5. The oxygen transfer efficiency is a critical component of the process because this determines the amount of air that must be supplied and therefore the amount of emitted water vapor which carries away latent heat of vaporization. For example, if the efficiency were 0.05 instead of 0.15 the reactor would operate at approximately 27° C (80° F) which is well below the thermophilic range. Biodegradable volatile solids destruction, however, would still amount to approximately 57 percent.

6. The use of oxygen would substantially reduce latent heat losses and therefore allow a higher operating temperature with greater volatile solids destruction for a given residence time.

It must be emphasized that the observations are extracted from the results of a computer model of aerobic thermophilic digestion. Andrews and Kambhu's presentation contains much more detail. However, the abbreviated presentation here serves to indicate reasonable engineering expectations which need experimental verification for specific wastes such as cattle manure.

CONCEPTUAL TREATMENT PROCESS

To help direct the experimental program for this study it was deemed important to lay out an overall treatment flow diagram that would contain the essential elements of a 500 cow pilot treatment operation. Figure 1 illustrates a conceptual treatment process. This process consists of thermophilic and mesophilic treatment followed by some method of solids separation such as vacuum filtration. Solids concentration in the thermophilic step must be maintained at a high level to maximize biological heat generation per unit volume, and therefore the feed approaches the composition of fresh manure. Additional wastewater from dairy washing operations may be added to dilute the raw manure if necessary. Residence time in the thermophilic stage is adjusted to achieve a reasonable balance between degree of stabilization and rate of stabilization. Very long residence times give a high degree of stabilization, but the rate of stabilization - equation (1) - is low because of low BVS concentration and even further reduced because of the lower reaction rate constant due to low temperatures from insufficient biological heat generation. A large reactor is needed to achieve a long residence time. On the other hand, very short residence times give a high rate of stabilization, but because the material is present in the reactor for a short period of time, there is little change between influent and effluent BVS.

Material from the thermophilic reactor passes to the mesophilic reactor for further stabilization. This reactor receives the benefit of a hot influent, but operates with a lower BVS concentration and a much lower temperature. This may be considered a finishing stage towards producing a well stabilized material. The final desired degree of stabilization establishes the residence time in the reactor. Some recycle of solids after the filtration step

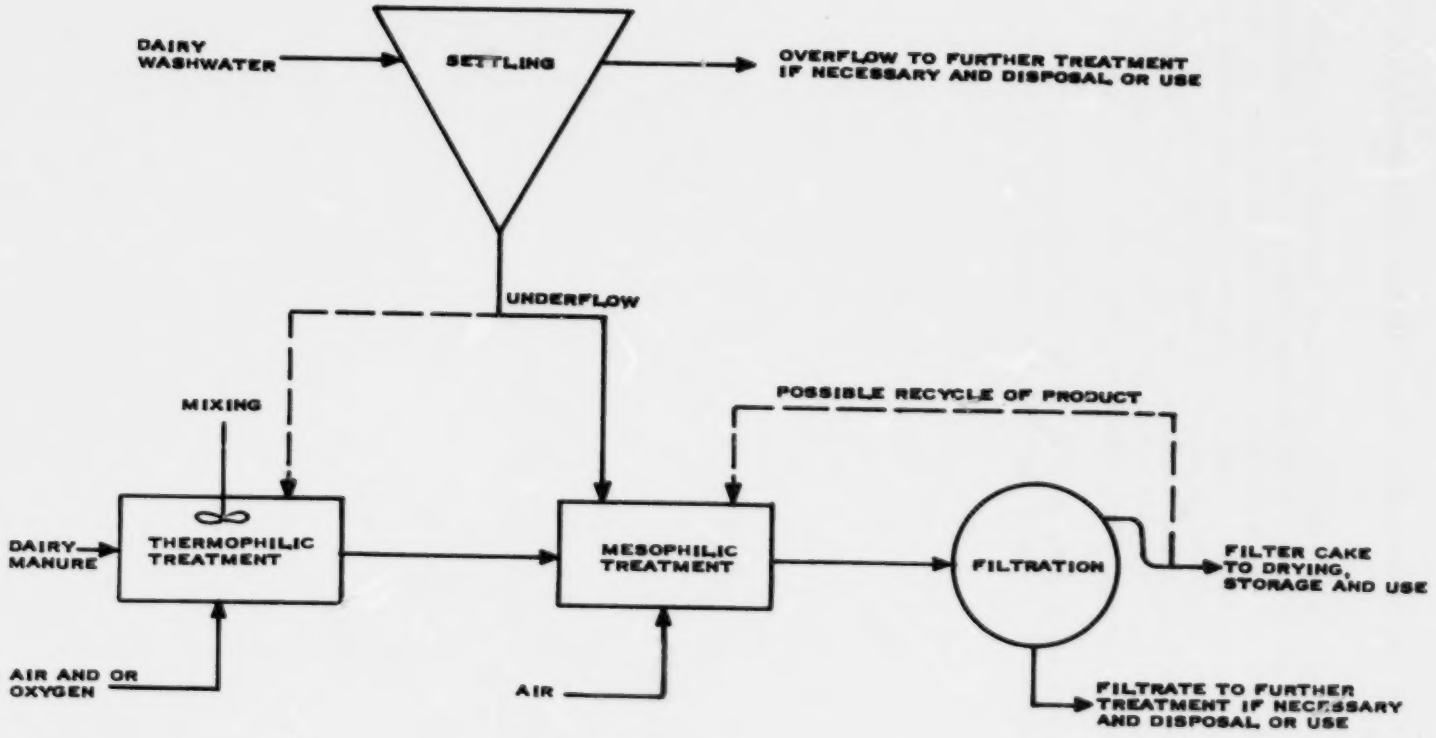

Figure 1. Conceptual thermophilic-mesophilic treatment process

may enhance the process by maintaining a higher concentration of microorganisms and BVS in the mesophilic reactor.

The filter cake from the filtration step is the major product of the process and is suitable for soil conditioning. In some cases the product could be spread directly; whereas, in other cases it may be desirable to dry and store the product for a period of time before use. The filtrate from the process has a high total dissolved solids (TDS) content as does the clarified dairy washwater. In some areas this water may be suitable for irrigating purposes. In the Santa Ana watershed, however, this water is undesirable for irrigating purposes, and therefore, in the absence of other suitable uses, the water has to be exported from the basin via a salt export facility that is planned to carry highly mineralized wastewaters to the ocean.[20, 21]

The thermophilic treatment step provides the bulk of the waste stabilization. It is the most novel part of the overall process and is therefore the primary focus of the current investigation.

SECTION V

EXPERIMENTAL EQUIPMENT AND PROCEDURES

BATCH REACTORS

A reactor was fabricated from a sturdy polyethylene container, 72 cm (28.5 in.) high and 44.5 cm (17.5 in.) inside diameter. Insulation consisted of three layers of fiberglass cloth, individually attached by resin, followed by a 2.5 cm (1 in.) layer of polyurethane and then two additional layers of fiberglass. A polyethylene snap-on lid covered the reactor. Holes were cut into this lid to fit equipment and provide access for feeding and sampling.

A mixer (Lightnin-variable speed, direct drive, continuous duty, 100 to 1725 rpm, 1/4 kW (1/3 hp), Model No. WS-1-VM with a ten-digit control dial) was supported above the reactor. A 1.27 cm (1/2 in.) stainless steel shaft passed through the reactor lid and was fitted with a 8.4 cm (3.3 in.) diameter stainless steel propeller to provide mixing. A bubble cutter at the surface of the liquid was also fitted to the shaft.

Air was supplied by a Bell and Gossett oilless air compressor [(Model No. SYC 9-1, 0.56 kW (3/4 hp), 3.1 l/sec (6.57 cfm) displacement, 2.3 l/sec (4.9 cfm) at 345 kN/m^2 (50 psi)]. Air was dispersed through a 30.5 cm by 5.1 cm (12 in. by 2 in.) diameter chromoglass ceramic air diffuser located on the bottom of the reactor. Airflow from the compressor to the diffuser was measured by a Brooks Sho-Rate rotameter, calibrated steel ball up to 0.57 l/sec (1.2 cfm).

A heat exchanger was constructed of 1.27 cm (0.5 in.) aluminum tubing, 4.26 m (14 ft) long, which was coiled inside the reactor. The heat source consisted of a portable, two-burner propane stove which heated a 15 l (4 gal) container of water. A 0.37 kW (1/20 hp) pump circulated heated water from the 15 l container through the heating coils and back to the container. Lines to and from the heating coils were sections of ordinary 1.6 cm (5/8 in.) garden hose. This system was controlled manually. Temperature of the reactor was measured with a stainless steel dial thermometer with stem that penetrated the reactor lid and extended into the contents of the reactor. Figure 2 illustrates the batch reactor.

Initially, one reactor as described above and later two such reactors were placed on a 3.7 m by 4.9 m (12 ft by 16 ft) concrete pad adjacent to a feeding corral. A roof was built over the pad to provide protection from rain and bright sunlight. A 6 m (20 ft) trailer adjacent to the corral and concrete pad served as field laboratory and office during the course of experimentation.

Freshly dropped manure was collected from the feeding corral prior to experimental runs. This was accomplished with a shovel and plastic buckets. Extreme care was taken to avoid contamination of fresh manure with dirt, sand or long pieces of straw. During some phases of the work, manure was comminuted with an Atomic Grinder (used for industrial garbage disposal). Hot water was added as needed to lubricate the grinding and prevent stoppage.

Manure was poured into the reactor to a level of 19 cm (7.5 in.) from the top of the reactor for a total of 79.5 l (21 gal). Maximum total solids content was limited to approximately 12 percent because of inability to adequately mix the contents at higher total solids content.

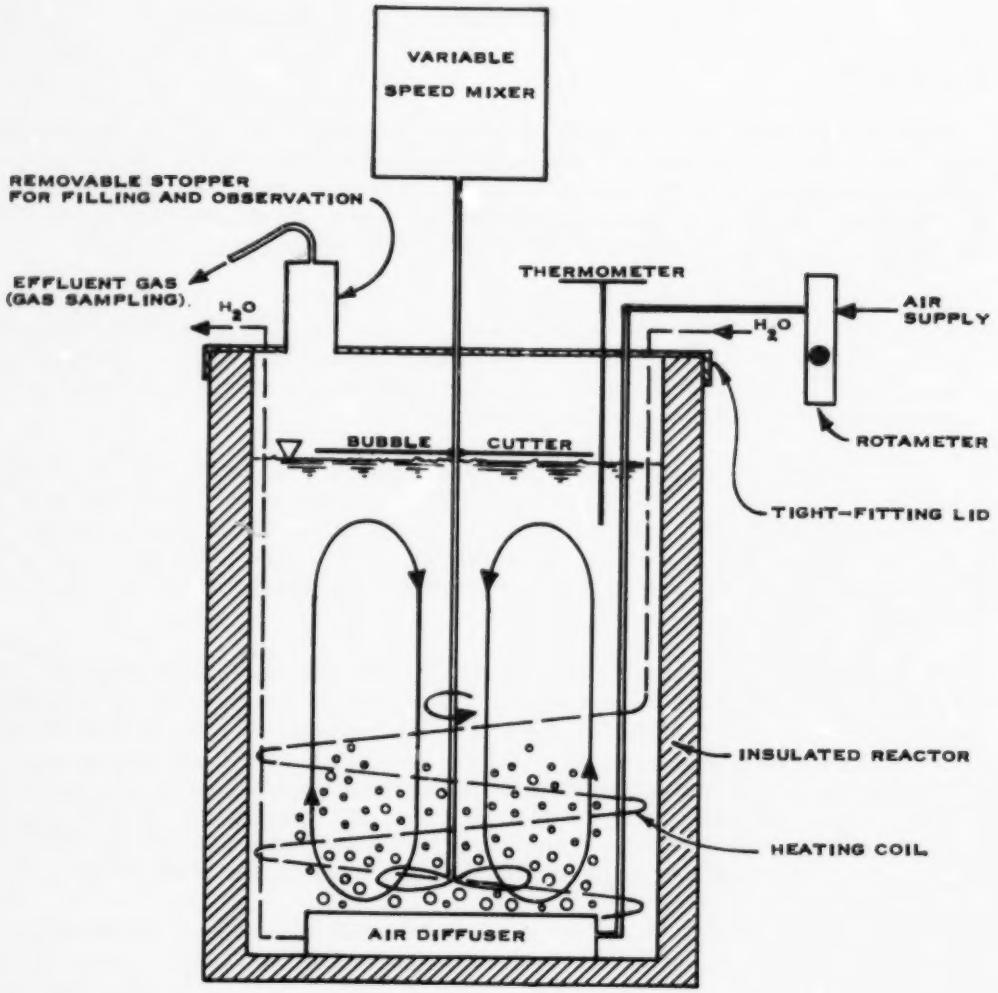

Figure 2. Schematic diagram of batch reactor

Batch studies were performed from November, 1972, to May, 1973. In general, the runs began by filling the reactor with fresh manure, assembling the top to the reactor, turning on the airflow, mixer and heat exchanger, and monitoring conditions while temperature increased from ambient to a desired level. It generally required 1 1/2 to 2 hours to bring the reactor to temperature. Variables studied over the course of the batch runs included airflow rate of 0.118 to 0.472 l/sec (0.25 to 1.0 cfm), reaction time of 5 hours to 7 days, mixing level of 5 to 10 dial position, temperature 45 to 60° C, and solids concentration of 6 to 12 percent total solids.

CONTINUOUS REACTIONS

Following the batch reactions, continuous reactions were initiated beginning in May and ending in August, 1973. A total of three thermophilic reactors were set up essentially as shown for the batch reactor in Figure 2, except that a spigot was added to the side of each reactor, approximately 30 cm from the bottom, for easy removal of reactor contents. Two reactors had the Lightnin variable speed mixers. The third reactor had a Model 5K122-1 Dayton continuous duty mixer, 0.37 kW (1/2 hp), 1750 rpm, prior to June 26 and thereafter a Model 6K375 Dayton Gearmotor mixer, 0.37 kW (1/2 hp), 40 rpm. The gearmotor mixer was ideal for slow stirring using flat stainless steel blades, 7.6 cm x 23 cm x 0.3 cm (3 in. x 9 in. x 1/8 in.) with a slight twist for lifting action. The heat exchangers for each reactor were connected in series with the circulating pump and hot water reservoir. After several incidents of the gas heater blowing out at night it was replaced with a 1650 W, two-burner electric hot plate. Manual adjustments were made to maintain reactors at desired temperature.

According to design a specified amount of material was removed from the reactors and fresh manure added twice daily. During high feed rates especially, the manure was heated in a 19 l (5 gal) bucket partially immersed in a heated, 115 l (30 gal) container of water. This minimized temperature shocks which would occur with addition of cold feed.

Three mesophilic reactors with contents of 95, 95, and 150 l (25, 25, and 40 gal) were fed once per day from the mixed discharge of the thermophilic reactors. There was no mixing other than that provided by the air supply and occasional manual stirring.

The single compressor used in the batch studies was fitted with a manifold to supply air for the three thermophilic and three mesophilic reactors. Airflow to each reactor was measured with a Brooks rotameter with ranges of 0 to 0.57 l/sec (0 to 1.2 cfm) for the thermophilic reactors and 0 to 7.6 l/sec (0 to 2.0 cfm) for the mesophilic reactors. During some of the testing oxygen from a cylinder was mixed with the air supply to a particular reactor. Quantity of oxygen was determined by observing gage changes on the cylinder and by oxygen measurements after mixing oxygen with a known flow of air.

During the course of the continuous runs, several changes and modifications were made to the air-diffusing apparatus. A summary of these modifications and changes with discussion is contained in the Appendix.

ANALYTICAL

Liquid samples for 5-day BOD, COD, total solids, volatile solids and other constituents were collected in 0.12 l plastic jars and sent to various laboratories for analyses in accordance

with Standard Methods for the Examination of Water and Wastewater. The bulk of the routine samples was analyzed at Chino Basin Municipal Water District Laboratory. Analyses for dissolved oxygen and pH were conducted on site with a YSI Model 54 dissolved oxygen meter and a Beckman Expandomatic Model 76 pH meter. The latter meter was checked periodically against a Leeds and Northrup Model 7413 pH meter.

Effluent gas samples from the reactors were collected in plastic bags approximately one liter in size and analyzed at the study site. The openings to the bags were sealed with 4 cm (1.5 in.) diameter corks with a 1.3 cm (1/2 in.) diameter hole bored through each cork. When the bags were full, another cork was placed over the hole to prevent mixing the contents of the bag with outside air. Initially samples were collected with the aid of a hand air pump which withdrew samples at a rate less than the airflow rate entering the reactor. However, it was soon realized that if the reactor top was sealed tightly enough there was no need for the hand air pump because the air pressure in the reactor was sufficient to inflate an empty bag.

One sample from each thermophilic reactor was collected at a time, and this was repeated as often as ten times per day. Samples were allowed to sit for a few minutes to equilibrate to room temperature while the oxygen probe and meter (Beckman Fieldlab Oxygen Analyses Model 1008) was adjusted to give a correct reading for a bag of saturated air. The oxygen probe was inserted through the hole in the cork sealed in the bag opening. The probe response changed over the course of a day or night, and therefore, it was necessary to determine the probe's response to changes in oxygen concentration in air. This was accomplished by diluting a sample of air with carbon dioxide so that the resulting oxygen concentration was 20 percent versus 21 percent for pure air. If the oxygen probe then indicated a difference in percent oxygen between the two (for example, 0.8 instead of 1.0), then subsequent measurements of differences between effluent samples and saturated air would be increased by the factor 1.0/0.8 and entered in the log book.

In addition to liquid and air-measurements, filtration tests were performed on samples taken from the reactors. Although some tests were qualitative, most were performed with quantitative results as the objective. The Eimco Corporation Filter Leaf testing apparatus was used for these tests.

EXPERIMENTAL DESIGN

The experimental program was initiated by laying out a work schedule for thermophilic digestion studies in the sequence: construction of facilities, heat balance studies, effect of temperature, effect of volatile solids concentration, effect of time of digestion, effect of concentration of oxygen, and effect of feeding and circulation variants. Mesophilic digestion studies, evaluation of by-products, and engineering development followed the thermophilic digestion studies in the work schedule, and the schedule showed overlap of the various elements.

A more detailed testing program was laid out for the continuous runs which began May 7. It was decided that a factorial type experiment would generate the most information in the shortest amount of time. Accordingly, after review of batch study results the following major variables were chosen for study in the thermophilic reactors:

1. feedrate - three levels corresponding to 2 1/2-, 5-, and 10-day hydraulic and solids residence time;

2. air/oxygen - four levels of 0.12, 0.24, 0.35 l/sec (0.25, 0.50, 0.75 cfm) of air, and 0.12 l/sec (0.25 cfm) of oxygen enriched air; and

3. temperature - two levels at 45-50^{o} C and 55-60^{o} C.

Two other important variables, solids concentration and amount of mixing, were held at relatively constant values. It was reasoned that the higher the solids concentration the greater the microbial thermogenesis per unit volume, and therefore, the solids concentration was kept at a reasonable maximum of approximately 10-12 percent total solids. Batch studies had shown high oxygen uptake rates for high mixing speeds with the propeller type mixers. Since mixing was going to be an important, major-cost item in the process, it was felt appropriate to hold mixing speeds to a low level but sufficient to give a good visual turn-over of the reactor contents. Because of physical constraints and the desire to provide minimal change in conditions for the microbial cultures, the sequence of runs were not completely random. Table 2 gives the conditions for the runs. Each run spanned one week with three runs performed simultaneously because three thermophilic reactors were available. Prior to starting the runs there was a trial period of three weeks in which the reactors were brought slowly to temperature. After completion of the runs shown in Table 2, two weeks of additional runs were conducted to verify results.

Three mesophilic reactors, labeled 1A, 2A and 3A, were operated simultaneously with the thermophilic reactors. The conditions for these remained constant throughout the experiment. Residence times were 10, 10 and 5 days, respectively, and solids contents were 12, 6 and 6 percent, respectively, for reactors 1A, 2A and 3A.

Energy balances for the thermophilic reactors were determined from physical measurements and calculations. During an afternoon when nothing except air was being fed or removed from the reactors, the supplemental heat supply was turned off and measurements taken to determine H_r, H_s, H_g, H_v, and H_m as defined for Equation 3 (page 8). H_m included only the direct input from mixing and H_l was zero because no liquid was flowing.

The rate of biological heat production, H_b, could then be calculated from Equation 3. In practice, however, the value of H_b could not be determined with great accuracy and therefore the total energy input, $H_b + H_m$, was calculated from Equation 3. An estimate of H_b itself was obtained from the oxygen utilization data assuming 1.0 kg of oxygen uptake is equivalent to 14,200 kJ (6,100 Btu) of energy released from biochemical oxidation.

The value of H_r was determined by measuring temperature changes in the reactor contents over time with an assumption that the specific heat of the contents was 3.9 kJ/kg-^{o} C (0.93 Btu/lb-^{o} F). This is a reasonable estimate based upon the type and concentration of organics present in the liquid. It was also assumed that the heat capacity of the reactor walls could be neglected in the heat balance calculations.

With a computer program a straight line was fitted by method of least squares through the temperature-time points to determine a rate of temperature change. From this

$$H_r = C \times W \, dT/dt \qquad (4)$$

where H_r = rate of sensible heat increase (or loss if negative), watts
C = specific heat of reactor contents, J/kg-^{o} C

Table 2. EXPERIMENTAL DESIGN FOR CONTINUOUS THERMOPHILIC REACTIONS

Week:	1	2	3	4	5	6	7	8
Reactor:	1 2 3	1 2 3	1 2 3	1 2 3	1 2 3	1 2 3	1 2 3	1 2 3
Temperature, °C:	— 45-50 —		— 55-60 —				— 45-50 —	
Feedrate level:[a]	1 1 2	1 1 2	3 1 2	3 1 2	3 2 1	3 2 1	3 2 3	3 2 3
Aeration level:[b]	2 3 4	1 4 3	1 3 2	2 4 1	3 4 1	4 3 2	2 1 3	1 2 4

[a]Level 1 corresponds to 7.6 liters per day (2 gpd)
Level 2 corresponds to 15.1 liters per day (4 gpd)
Level 3 corresponds to 30.3 liters per day (8 gpd)

[b]Level 1 corresponds to 0.07 l/sec (0.15 cfm) of air and 0.05 l/sec (0.10 cfm) of oxygen
Level 2 corresponds to 0.12 l/sec (0.25 cfm) of air
Level 3 corresponds to 0.34 l/sec (0.50 cfm) of air
Level 4 corresponds to 0.35 l/sec (0.75 cfm) of air

W = weight of reactor contents, kg
dT/dt = rate of temperature increase (or decrease if negative), ^{o} C/sec

Customary units were utilized in the analyses, and results were later converted to the modern metric system as presented here. Temperatures were actually measured and recorded in ^{o} C and converted to ^{o} F only within a computer program set up to perform the routine heat balance calculations.

Heat losses to the environment through the reactor wall were determined by:

$$H_s = U \times S(T_r - T_s) \quad (5)$$

where H_s = rate of heat loss to the surroundings, watts
U = overall heat transfer coefficient, J/m^2 sec-^{o} C
S = reactor surface area, m^2
T_r = temperature of reactor, ^{o} C
T_s = temperature of surroundings, ^{o} C

In determining the quantity U x S the reactors were filled with 79.5 l (21 gal) of hot water and allowed to stand in order to observe temperature loss with time. The water was agitated periodically to prevent temperature stratification but this provided no significant energy input. Since all other energy inputs and outputs were zero, H_s was equated to H_r and the quantity U x S determined thereby.

The heat lost with the airstream leaving the reactor consisted of sensible and latent heat. Airflow rate, ambient temperature, and exit temperature of the air leaving the reactor provided the necessary physical measurements:

$$H_g = Q \times (T_e - T_s) \times 1.20 \times 1000 \quad (6)$$

where H_g = rate of sensible heat lost in airstream, watts
Q = flow rate of air standardized to one atmosphere and 21^{o} C, m^3/sec
T_e = exit air temperature leaving the reactor, ^{o} C
T_s = temperature of surroundings, ^{o} C

The constants in the formula represent density of air of 1.20 kg/m^3 (0.075 lb/scf) at standard conditions and specific heat of air of 1000 J/kg-^{o} C (0.24 Btu/lb-^{o} F).

The latent heat of varporization lost from the reactor was:

$$H_v = W \times 2.35 \times 10^6 \times 0.744 \quad (7)$$

where H_v = rate of latent heat lost in water vapor, watts
W = flow rate of water vapor, m^3/sec, corrected to standard conditions and calculated from saturation vapor pressure (a function of exit air temperature) and flowrate of air.

The constants in formula (7) represent latent heat of vaporization for water of 2.35 x 10^6 J/kg (1010 Btu/lb) and density of water vapor of 0.744 kg/m^3 (0.0464 lb/scf) corrected to standard conditions. The basic formula used in the computer calculations to determine the vapor pressure of water was:

$$\log (Vp) = 0.00648 \times T - 3550.44/T - 6.1213 \times \ln (T) + 46.227 \quad (8)$$

where V_p = vapor pressure of water, mm Hg
T = absolute temperature, ^{o}K
log = logarithm to the base 10
ln = natural base logarithm

The energy input from mixing was more difficult to measure. Conceptually it could be determined as follows:

$$H_m = P \times E \times V \times A \quad (9)$$

where H_m = rate of energy input from mixing, watts
P = power factor, expressed as a fraction
E = efficiency, expressed as a fraction
V = voltage, volts
A = amperage, amperes

The limitations of this approach arise from the difficulty in estimating the power factor and efficiency. An alternate approach of measuring torque and angular speed of the mixer shaft was rejected because of equipment costs and difficulty in obtaining true torque readings even with the appropriate equipment. For the type of motors used with the mixers the maximum value of P x E is approximately 0.3. This then set a maximum energy input from mixing when the amperage and voltage were measured for each mixer. The two Lightnin mixers showed reduced amperages at lower speeds, and therefore, it was possible to better estimate the net energy input to the reactors from mixing. The third mixer remained at a fixed amperage under different loads, and therefore, it was more difficult to estimate net energy input. A measure of the wattage indirectly would give a measure of V x A x P but would still require an estimate of E, and therefore, a wattmeter would contribute towards obtaining H_m but could not eliminate the need for making a judgment on an unknown factor in the above equation.

To summarize the procedure for obtaining an energy balance, the quantities H_r, H_l, H_v, H_g, and H_s of Equation 3 were determined without complication. Therefore, the sum of the quantities H_m and H_b was calculated from Equation 3. A maximum value and an approximation of H_m was obtained through Equation 9, and this allowed an estimate of H_b, the energy generation from biochemical oxidation. An independent estimate of H_b was obtained from oxygen utilization data assuming that oxygen utilization is related directly with energy generation. Therefore, energy balance results were limited by the precision with which specific components of Equation 3 could be determined and by the accuracy of the assumption that one kilogram of oxygen utilized results in 14,200 kJ of energy released during biochemical oxidation.

SECTION VI

EXPERIMENTAL FINDINGS AND DISCUSSION

MANURE CHARACTERIZATION

Fresh dairy cow manure is variable in character as evidenced by results of analyses presented in Table 3. The bulk of the analyses were performed during the period of May through August, 1973. Averages and variations are shown for various parameters. A small amount of water was added to the manure collected from the feeding pens in order to aid in mixing the entire batch before taking a sample. Therefore, the values for percent total solids (TS) and quantities given in grams per liter are slightly lower than they would be for undiluted manure without urine mixed in.

The variation shown in volatile solids, 5-day BOD, COD, and other parameters, is due, in large part, to the variation resulting from sampling and analytical procedures as evidenced by results of replicate samples. However, much of the variation is also estimated to come from the inherent variability of manure. This variability is expected to be due to the cow feed and to environmental factors which affect the metabolism of cows.

Table 4 gives a compilation of dairy cow manure characteristics as reported by other investigators and substantiates that there is considerable inherent variation in the characteristics of manure. This variation cannot be disregarded in design of manure processing facilities.

During this study the feed to the cows varied in composition from time to time. No attempt was made to control the normal dairy operation. The individual cow ration was approximately 23 kg (50 lb) per day on a dry weight basis. This ration consisted of approximately 11.5 kg (25 lb) of alfalfa hay and 11.5 kg (25 lb) of grain. However, tomato pulp, brewers grain and orange hulls were also fed when available as a partial substitute for hay and grain, always with the objective of a total ration of approximately 23 kg per cow per day. The typical dairy cow ration is presented in Table 5.

Table 6 shows analyses of a 38 l (10 gal) sample of manure that had been aerated for a seven-week period with no additions except water to maintain a solids concentration of approximately 6 percent. Tables 3, 4, and 6 indicate some characteristics of dairy cow manure that relate to biological treatment of the manure. The low ratio of 5-day BOD to COD, in the range of 0.1 to 0.3, indicates the resistance of the organic fraction of manure to biological degradation. This resistance is attributed to lignins and cellulosic material. The simple, extended aeration of a sample for 7 weeks indicated a substantial reduction in 5-day BOD, some reduction in soluble COD, but no reduction in total COD. Thus giving further evidence to the resistance of the bulk of the waste to biological treatment. In fact, the results indicated an increase in total COD which is difficult to exp! .in other than to state that it may be an error. This result was not duplicated, but a possible explanation may lie within the COD test itself. Some of the organics may not be thoroughly oxidized when the COD test is performed on raw manure. After aeration for an extended period of time, these organics may be partially broken down physically and biochemically and be more susceptible to the strong oxidizing agent in the COD test. This possibility places an added burden upon the interpretation of COD results. An appropriate value of BVS to use in the mathematical model presented in Section III is not readily apparent from waste

Table 3. EXPERIMENTAL CHARACTERIZATION OF FRESH DAIRY COW MANURE

Component	Average	Range	Standard deviation	Coefficient of variation	Number of samples
Total solids, percent of manure	15.4	12.9 - 19.8	2.17	0.14	21
Volatile solids, percent of solids	86.1	76.7 - 91.8	3.0	0.035	21
Total COD, gms/l	149	81 - 284	57	0.38	17
Soluble COD, gms/l	33	19 - 53	10	0.30	16
Total BOD_5, gms/l	16.1	8.6 - 21.5	3.5	0.22	12
Soluble BOD_5, gms/l	9.3	4.6 - 14.4	3.0	0.32	11
pH	6.2	5.2 - 6.8	0.5	0.08	12
Total COD, gm/gm TS	0.96	0.56 - 1.48	0.30	0.31	17
Total COD, gm/gm VS	1.10	0.66 - 1.69	0.34	0.31	17
Soluble COD, gm/gm TS	0.22	0.11 - 0.33	0.07	0.33	16
Total BOD_5, gm/gm TS	0.105	0.06 - 0.13	0.025	0.24	12
Total BOD_5, gm/gm VS	0.123	0.06 - 0.16	0.030	0.25	12
Soluble BOD_5, gm/gm TS	0.062	0.03 - 0.10	0.023	0.36	11
Total BOD_5/Total COD, gm/gm	0.108	0.04 - 0.15	0.038	0.35	10
Soluble BOD_5/Soluble COD, gm/gm	0.270	0.16 - 0.41	0.075	0.27	9
Total nitrogen (N) percent TS	2.8	2.6 - 2.9			2
Soluble phosphorous (P), percent TS	0.25	0.17 - 0.32			4
Total potassium (K), percent TS		0.5 - 5			7
Heating value, kJ/kg	19,000				1

Table 4. REPORTED DAIRY MANURE CHARACTERISTICS[a]

	Range	Typical
Total solids, percent of manure	10 - 16	13
Volatile solids, percent of solids	72 - 85	80
Total COD, gm/gm TS	0.8 - 2.1	1.0
Total BOD_5, gm/gm TS	0.06 - 0.18	0.18
Total BOD_5, gm/gm VS	0.13 - 0.39	0.23
Total BOD_5/Total COD, gm/gm	0.08 - 0.23	0.17
Nitrogen (N), percent TS	2.8 - 5.5	4
Phosphorous (P), percent TS	0.4 - 0.5	0.5
Potassium (K), percent TS	0.3 - 3.0	1.7

[a]See references 15, and 22-32

characterization measurements. As indicated in Section III, the complicated biochemical processes probably cannot be adequately approximated by a single reaction, but requires two to make a reasonable model. The BVS for an overall fast reaction acting upon readily biodegradable material appears to be in the vicinity of 15 percent of the volatile solids. The BVS for the second, slow reaction could be an additional 75 percent of the volatile solids. The combination thereby would indicate a total BVS of 90 percent of the volatile solids which corresponds to the volatile solids reduction noted during a long period of composting. However, this latter estimate of 75 percent cannot be deduced from the data presented above and may be substantially in error in a liquid system such as that studied herein, as opposed to a moist but solid-phase, conventional composting operation. Even with substantially more BVS to work upon, the slower reaction would not contribute significantly to biological heat generation because the rate is very much lower than that of the faster reaction. Therefore, for practical purposes in terms of oxygen utilization and biological heat generation it appears that the slower reaction can be neglected.

Table 5. TYPICAL DAIRY COW RATION

Alfalfa - 11.5 kg (25 lb) per cow per day	
Moisture, percent	9
Crude protein, percent	17
Digestible protein, percent	14
Modified crude protein, percent	25
Crude fiber, percent	25
Total digestible nutrients	52
Molybdenum, ppm	3.8
Copper, ppm	11.0
Feed concentrate[a] - 11.5 kg (25 lb) per cow per day	
Crude protein, percent	≥ 13.5
Crude protein NPN, percent	≤ 4.0
Crude fat, percent	≥ 3.0
Crude fiber, percent	≤ 7.0
Ash, percent	≤ 7.0
Added minerals, percent	≤ 2.0

[a]Ingredients include orange pulp, almond hulls, hominy pellets, cane molasses, urea, sulphur, rolled milo, brewers dried grain, dairy concentrate, and salt.

An important consequence of the relatively low BVS of dairy manure is that it precludes achieving a high BVS concentration in the reactor. For example, in order to achieve a BVS concentration of 3 percent a total solids concentration on the order of 20 percent would be required. Such a mixture is hardly liquid. In order to maintain a liquid system which can be mixed without difficulty, the maximum BVS concentration will be limited to approximately 2 percent of the total liquid. Following the rationale of Andrews and Kambhu[16,17], it is evident that there would be a definite upper limit to the rate of heat generation and, therefore, an upper limit of operating temperature to the low thermophilic range.

BATCH REACTIONS

Data collected from batch reactions invited a challenge for interpretation in terms of response of dependent variables such as oxygen uptake rate to independent variables such as temperature, mixing, and airflow rate. Part of the perplexity arose from variations in percentage oxygen depletion indicated by the oxygen meter for the gas samples. Over relatively short time periods (on the order of an hour) large changes were often noted in the

Table 6. RESULTS OF LONG TERM AERATION OF MANURE[a]

	Average manure	Measured at start of aeration	Measured after 7-weeks aeration
Volatile solids, percent of solids	86.1(21)	86.1(2)	84.9(3)
Total COD, gm/gm TS	0.96(17)	0.77(1)[b]	1.26(2)
Soluble COD, gm/gm TS	0.22(16)	0.32(1)	0.20(2)
Total 5-day BOD, gm/gm TS	0.105(12)	-	0.03(2)
Soluble 5-day BOD, gm/gm TS	0.062(11)	-	0.014(2)

[a]Numbers in parenthesis following the entries in the table show the number of samples that were averaged to obtain the entry.

[b]Questionable result.

percent oxygen depleted in the gas samples, and a major enigma throughout the experimental work was whether such changes reflected true changes or were simply variations in the response of the oxygen meter. The oxygen probes were replaced periodically, the instrument was tested by the manufacturer to insure that it worked properly, and the instrument was checked constantly against a known concentration of oxygen. In view of these precautions and other precautions to insure reliable samples it was concluded that at least a substantial portion of the variation was true variation within the reactor system. Because of large variations the oxygen uptake values shown in Table 7 must be viewed as crude averages. These oxygen uptake rates were obtained by inspecting a large number of points and choosing what appeared to be reasonable averages. It did not appear that a more precise method of obtaining oxygen uptake rates from the oxygen data would contribute to evaluation of the process.

An explanation for some of the variation may relate to changes in the air distribution pattern within the reactor. Accumulations of solids on the aerator were noted after every run. Mixing action was an important factor in achieving higher oxygen uptake rates and it is reasonable, therefore, that the direction of the airstream relative to the mixing propeller had a large effect upon getting oxygen into solution which is an important prerequisite to oxygen utilization.

Table 7. OXYGEN UPTAKE FOR BATCH REACTIONS

Date	Length of reaction, hrs	Temperature range[a]	Total solids, percent	Mixing speed[c]	Airflow, l/sec	Oxygen uptake, ml/sec	Comment on feed to reactor
15 November	6.7	H	-[b]	5	0.12	2	comminuted
21 November	5.8	H	-[b]	5	0.24	1	comminuted
22 November	7	H	-[b]	5	0.24	1	comminuted and compost added
6 December	5.7	H	-[b]	5	0.12	2	comminuted
12 December	6.5	H	12	5	0.24	3	comminuted
13 December	6.8	H	15	10	0.24	3	compost added
19 December	6	H	10	10	0.12	1	comminuted and N-source added
20 December	7.3	L	11	10	0.24	3	as collected
26 December	7.3	L/H	14	10	0.24	2/3	1/3 preceding product
27 December	8.5	L/H	15	10	0.24/0.47	2/4	as collected
2 January	7.7	L	15	10	0.47	4	1/3 preceding product
3 January	5.2	H	14	10	0.47	6	1/3 preceding product
4- 5 January	48	L	15	10	0.47/0.24	6/4	1/3 preceding product
10-12 January	56	H/L	15	10/5	0.24/0.12	6/0.5	all preceding product
16-18 January	47	H/L	15	10/5	0.24	5/0.5	2/3 preceding product
18-19 January	32	LL	–	10	0.12	0.5	comminuted
23-26 January	72	H/L	–	10	0.24	4/3	all preceding product

[a]Temperature range: H = above 55° C but generally less than 60° C; L = between 45° and 55° C; LL = below 45° C; HH = between 60° and 70° C.
[b]Samples not taken but values subsequently estimated to be less than 10 percent total solids.
[c]Mixing speed can be set from 1 to 10 on Lightnin mixer.
[d]Air enriched with 0_2 to approximately 32 percent 0_2.
[e]Air enriched with 0_2 to approximately 42 percent 0_2.

Table 7. (Continued)

Date	Length of reaction, hrs	Temperature range[a]	Total solids, percent	Mixing speed[c]	Airflow, l/sec	Oxygen uptake, ml/sec	Comment on feed to reactor
30-31 January	24	H	–	10	0.24	2	2/3 preceding product comminuted and 1/3 preceding product
7-10 February	72	H	–	10	0.24	4	comminuted and 1/3 preceding product each a.m.
13-16 February	80	HH/H	–	10	0.24	4/2	comminuted and 1/3 preceding product each a.m. on 21 and 22 February
20-24 February	96	H	13	10	0.24	2/4	1/3 preceding product
27-14 March	360	H	13	10	0.24/0.12	2/1	all preceding product
15-16 March	31	H	14	10	0.12	2	comminuted and 3.8 l preceding product
20-23 March	72	H/L	14	10	0.12	1/0.5	comminuted
10-11 April	24	HH	12	10	0.12	2	comminuted
10-11 April	26	HH	13	10	0.24	4	as collected
12-13 April	30	HH	16	10	0.24	4	as collected and diluted
12-13 April	24	HH	8	10	0.24	4-8	as collected
18-20 April	55	HH	13	10	0.12	5	as collected
18-20 April	55	HH	13	10	0.12[d]	7	as collected
25 April	32	HH	12	10	0.12	6	as collected
25 April	32	HH	12	10	0.12[e]	12	

[a]Temperature range: H = above 55° C but generally less than 60° C; L = between 45° and 55° C; LL = below 45° C; HH = between 60° and 70° C.
[b]Samples not taken but values subsequently estimated to be less than 10 percent total solids.
[c]Mixing speed can be set from 1 to 10 on Lightnin mixer.
[d]Air enriched with 0_2 to approximately 32 percent 0_2.
[e]Air enriched with 0_2 to approximately 42 percent 0_2.

The average values do not indicate trends observed during the course of the reactions. Generally, there was greatest oxygen uptake immediately after the reactions were brought up to temperature. For the longer runs, therefore, the oxygen uptake rates tended to decrease as the reactions proceeded.

Reactions were of too short duration in general to observe any significant change in COD or BVS. However, some physical changes were apparent in the manure after the reactions. The product was more fluid which could be attributed to physical break-down of fibrous materials as a result of vigorous mixing. For a certain period of time the product also possessed an innocuous quality as evidenced by lack of odors and lack of attraction for flies. In fact, the nature of the product suggested that it had been sterilized which lead to questions about the nature of the reactions, such questions as whether the oxygen uptake could be due to chemical reactions rather than biochemical reactions. In support of the predominance of chemical reactions are the following considerations:

1. Pasteurization achieves its effect by raising temperatures rapidly to a level of approximately 62° C (143° F) and maintaining this temperature for 30 minutes. In the above batch reactions temperatures were raised at the rate of 15° to 30° C per hour to reaction temperature and held generally at that temperature for the duration of the run. Such a procedure would be expected to kill all but the hardiest thermophilic and thermoduric bacteria.

2. The initial rapid oxygen utilization rate observed when reaction temperatures were reached belies an expected utilization rate which would occur if there were initially only a small number of aerobic thermophiles which needed to multiply before a relatively high utilization rate was attained.

3. Wet chemical oxidation has been observed at temperatures as low as those in the above batch reactions.[33] It appears plausible, therefore, that large energy input through the propeller blades could create sufficiently high temperatures and pressures adjacent to the propeller to allow wet chemical oxidation.

4. If bacterial growth were responsible for the oxygen uptake, it would be reasonable to assume that there would be plenty of bacteria present in the product to induce flies and cause other nuisances in view of the fact that plenty of BVS remained in the product. The lack of fly attraction and odors suggests that there was not a large biological population present. When the material was left to stand for a considerable length of time, fly attraction and odors began to occur, suggesting that a bacterial population was being reestablished.

5. For many of the reactions, product from the previous reaction was added at the start. Also, for two reactions (22 Nov. and 13 Dec.), dry, composted manure was added, and in another instance (19 Dec.), urea and calcium nitrate were added to the feed of the reactions. If the oxygen uptake resulted primarily from biochemical activity, then one would expect substantial differences in oxygen uptake rates as a result of these varying conditions. Substantial differences could not be identified from the data collected, and therefore, doubt is cast upon the presence of substantial biochemical activity. However, it is questionable whether any of these additions to the reactor could influence biological activity within the short periods of the tests.

The data presented in Table 7 provides some indication of apparent reaction rates. For example, a first order reaction rate constant can be calculated based upon the data with certain assumptions presented earlier in Section IV. An oxygen uptake rate of 5 ml/sec and a reactor containing readily degradable material equivalent to approximately 1.8 kg of oxygen would indicate a first order reaction rate constant of 0.3 day^{-1}. However, the range of uptake rates indicate a wide range for the rate constant between 0.06 to 0.7 day^{-1}. The lower value is well within the range of biological activity, but the higher value appears to be out of the range of biological activity and defies an easy explanation unless it be in terms of chemical oxidation or possibly oxygen absorption which only partially oxidizes the organic material and does not significantly reduce the weight of volatile solids. This latter suggestion may help explain why no significant volatile solids reductions were observed even after several days of apparently high oxidation rates.

CONTINUOUS REACTIONS

Each thermophilic reactor was filled with hot water and allowed to cool for a several-hour period in order to determine the heat loss through the reactor walls for a differential temperature between the reactor and the surroundings. The results of these experiments showed that heat loss amounted to 12.0, 12.6 and 13.0 kJ/hr-^{o} C (6.32, 6.65 and 6.85 Btu/hr-^{o} F) for reactors 1, 2 and 3 respectively. These values and various temperatures were applied to the energy balance equations discussed in Section V, and thereby an estimate of the energy or heat (these are used interchangeably here) generated during thermophilic reactions was obtained. The total energy generation includes biological heat production and mixing energy input to the reactors and this total is shown in Table 8 for each of the thermophilic reactions. During the latter weeks of experimentation more than one determination was made and these are shown in Table 8. Because of the difficulty in estimating mixing energy input, it was not possible to separate the total energy generation into biological and mixing components, although considerable effort was expended in attempting to do so. However, another approach based on heat released per unit of oxygen utilized, as discussed in Sections IV and V, gave an independent estimate of the biological component of the total energy generation. During the period that energy balances were being determined, oxygen utilization measurements were also taken, and the resulting biological energy generation values estimated from these oxygen measurements are also shown in Table 8. In three specific cases the biological energy generation exceeded the total energy generation, giving unreasonable results. In these cases, the biological energy generation was assumed equal to the total energy generation in subsequent analyses. An explanation for two of the three values could be simply that because of inherent error of measurement some overlap is expected, in that biological energy generation exceeds the total very slightly. In the third situation, a reaction in which pure oxygen was involved, an explanation is more elusive. Conceivable explanations include:

1. Sampling error for that reactor during oxygen measurements - perhaps there was substantial mixing with ambient air of gas leaving the reactor;

2. Error in analysis with the oxygen meter although all other analyses appear reasonable;

3. Peculiar absorption of oxygen in the reactor which did not oxidize material to produce anything near 14,200 kJ/kg (6,100 Btu/lb) of oxygen absorbed.

Table 8. ENERGY GENERATION IN CONTINUOUS REACTIONS

Week	Reactor	Reaction number	Total energy generation, kJ/hr	Biological energy generation, kJ/hr
1	1	14	170	70
	2	15	160	60
	3	20	370	190
2	1	13	400	290
	2	16	250	120
	3	19	320	130
3	1	9	310	(840)
	2	3	210	130
	3	6	250	130
4	1	10	150	80
	2	4	110	60
	3	5	110	90
5	1	11	180	130
	2	8	150	120
	3	1	90	50
6	1	12	220/300	110/140
	2	7	270/440	90/160
	3	2	260/130	40/40
7	1	22	320/260	110/130
	2	17	740/450	590/220
	3	23	60/60	50/(70)
8	1	21	610	360
	2	18	250	110
	3	24	220	70
9	1	–	420/520/470	270/340/270
	2	–	370/370/330	270/230/210
	3	–	630/610/520	560/370/370
10	1	–	590/560/510	270/260/240
	2	–	420/390/300	150/260/(350)
	3	–	410/380/390	60/ 80/120

This latter explanation would be the most disturbing because it affects a basic assumption in the analysis. Although this isolated result does challenge the basic assumption of approximately 14,200 kJ/kg of oxygen, the analyses proceeded utilizing this assumption.

An inspection of Table 8 indicates the dependence of biological activity upon the mixing energy input. Higher rates of biological activity are associated with larger mixing energy input. Aerobic biological activity depends upon receiving adequate quantities of oxygen, and the results confirm that mixing is important in the present system for producing substrate-organism-oxygen contact. Throughout the series of experiments, especially the first 8 weeks, the mixing input was minimized to provide no more than the amount of mixing needed to keep the reactor contents well mixed. This was a subjective evaluation performed for each reaction. It was apparent prior to the start of the continuous experiments that mixing would be a substantial portion of the overall cost of operation in a large scale system, so a conscious effort was made to minimize the amount of mixing. During weeks 9 and 10, following the 8-week, factorial experiment, an increase in mixing energy was allowed and the results show an increase in biological activity.

In order to examine the effects of aeration, feedrate, and temperature upon biological activity, the individual runs need to be separated according to the patterns presented in Table 9. For example, to compare the effects of temperature upon any dependent variable such as biological heat generation, reactions 1 through 12 are compared with reactions 13 through 24. All the basic 24 reactions conducted during the 8-week period are used to examine the effects of one independent variable upon any dependent variable such as biological activity. Table 10 summarizes the analyses for effects of aeration, feedrate and temperature upon biological energy generation. Table 10 shows that aeration level A_1 (0.05 l/sec of pure oxygen and 0.07 l/sec of air) produces far greater energy generation than does any other aeration level. (The question of statistical significance is addressed later in this Section.) This result suggests that organism activity is limited by the oxygen that can be transferred to the solution. The lack of substantial effects among A_2, A_3 and A_4 suggests that the aeration system employed herein was not effective in transferring proportionately increased quantities of oxygen from air at airflow rates above the 0.12 l/sec level.

Feedrate produced a smaller effect upon biological activity, but the data do show an increase in activity between F_1, the lowest feedrate, and F_2, the intermediate feedrate. There is essentially no difference between F_2 and F_3, the highest feedrate. This result might indicate that available substrate begins to control biological activity somewhere between 5 and 10 days residence time (hydraulic and solids residence time were identical during the experiment).

The effect of temperature is indicated by the difference in energy generation between T_1 and T_2. Apparently a 10° C rise from 45-50° C to 55-60° C produces approximately a 40-percent increase in energy generation. However, because of the oxygen-limited nature of many of the reactions, this value probably does not reflect the true increase in biological activity that would occur with unlimited oxygen.

Following the factional group of experiments, the thermophilic reactions were continued an additional two weeks. The six reactions were too few to establish definitive conclusions, but Table 11 shows the conditions of the reactions together with the apparent biological activity. Feedrate was 11.4 l/day (3 gpd) or 7 days residence time for each reactor except for reactor 3 which received no feed during the last week. The effect of no feed was reduced

Table 9. REACTIONS INVOLVED AT LEVELS OF INDEPENDENT VARIABLES

Independent variable	Reaction numbers involved at level of variable
Aeration level	
A_1 (0.12 l/sec)[a]	1, 5, 9, 13, 17, 21
A_2 (0.12 l/sec)	2, 6, 10, 14, 18, 22
A_3 (0.24 l/sec)	3, 7, 11, 15, 19, 23
A_4 (0.35 l/sec)	4, 8, 12, 16, 20, 24
Feedrate[b]	
F_1 (7.6 l/day)	1, 2, 3, 4, 13, 14, 15, 16
F_2 (15.1 l/day)	5, 6, 7, 8, 17, 18, 19, 20
F_3 (30.3 l/day)	9, 10, 11, 12, 21, 11, 23, 24
Temperature	
T_1 (45-50° C)	1 through 12
T_2 (55-60° C)	13 through 24

[a]0.07 l/sec of air and 0.05 l/sec of oxygen.

[b]Feedrates F_1, F_2, and F_3 correspond to 10.5, 5.25 and 2.63 days retention time, respectively.

biological activity which remained fairly constant for the entire week, and a 4-percent reduction in the volatile solids fraction was recorded at the end of the week.

Lower solids concentration produced little net effect upon biological activity. This may indicate a combination of greater solubility of substrate and increased oxygen transfer efficiencies at lower total solids concentration. Another possibility is that there is some inherent limitation to the rate at which the organisms can utilize the substrate. It is apparent that interpretation of results is hampered by the complexity of the system. There are intimate relationships among organisms, substrate and oxygen. The substrate may be bound with the manure solids and become available upon comminution of the solids by the mixer. It is also possible that the propeller mixer tends to destroy bacterial cells at higher mixing rates. Then too, the relative location and condition of the mixer and aerator could considerably influence reaction rates.

Table 10. EFFECT OF VARIABLES ON BIOLOGICAL ENERGY GENERATION

Variable	Energy generation, kJ/hr
Aeration level:	
A_1	251
A_2	92
A_3	106
A_4	115
Feedrate:	
F_1	103
F_2	162
F_3	157
Temperature:	
T_1	116
T_2	166
Average for all reactions	141

Considerable effort went towards modifying the aeration equipment and the basic mixing agitator to increase the biological activity of the thermophilic reactions. Several shapes of aerators, fabricated from plastic tubing, and several agitators, including some large, slow-turning types, were experimented with. Any substantial improvement over the basic diffuser and propeller could not be detected. Some details of these experiments are included in the Appendix.

Table 12 presents some of the stabilization measures determined during the end of each reaction just before conditions were changed for a subsequent reaction.

The most significant observation for all of the reactions is that thermophilic treatment produced very minimal stabilization. The effect of variables upon stabilization, as measured by the ratios of soluble COD and soluble 5-day BOD to the total solids content, is shown in Table 13.

Table 11. REACTION CONDITIONS DURING WEEKS 9 AND 10

Week	Reactor	TS concentration, percent	Aeration level	Feedrate, l/day	Temperature °C	Biological energy[a] kJ/hr
9	1	10	A_1	11.4	59-61	295
	2	7	A_2	11.4	56-61	235
	3	8	A_3	11.4	57-61	430
10	1	10	A_2	11.4	58-63	255
	2	7	A_1	11.4	57-64	255
	3	7	A_3	0.	44-47	85

[a]Averages of values shown in Table 8.

The differences indicated for the various aeration levels were not significantly different. The differences shown for feedrates were significantly different and provide some insight to what is occurring in the reactions. The low feedrate showed higher soluble BOD and COD values in the product than did higher feedrates. This surprising result indicates that the longer residence time allowed BOD and COD in the reactor to become soluble faster than it could be biologically degraded. A higher temperature increased the amounts that became soluble. In fact, there was more soluble COD and BOD in the product on the average than there was in the raw manure. Also, there was more total COD indicated in the product than in raw material. This could be explained in terms of limitations of the COD test which allowed more complete chemical oxidation of organic material after it passed through the thermophilic reactors.

A summary of an analysis of variance is shown in Table 14. The F test was employed to determine whether differences measured as effects were significant or could be attributed to statistical effor. For the biological energy generation analysis, the effects due to aeration, feedrate, and temperature were significant at approximately the 99-, 85-, and 90-percent levels, respectively. This means that the observed differences would occur by chance alone no more than 1, 15 and 10-percent of the time, respectively. The differences in stabilization as affected by aeration levels could be attributed to statistical error. For soluble-COD differences the effects due to feedrate and temperature were significant at approximately the 85- and 99.5-percent levels respectively. For soluble-BOD differences the effects due to feedrate could be attributed to statistical error, but the effects due to temperature were significant at approximately the 97.5-percent level.

Other measurements and observations should be noted regarding the thermophilic reactions. The pH was higher in the reactors than it was in the raw manure. Values generally ranged above pH 7.0, and in no case was the pH below 6.6, so pH of the reactions was not considered a limitation to the biological activity. There was approximately a one-quarter reduction in the total nitrogen values from the raw manure. There were isolated incidents when an ammonia smell could be detected from the reactors. There was a short period of time of two or three days at the start of the experimentation when the three thermophilic reactors began to smell somewhat sour. An increase in mixing energy and a continual clean-up of the aerators throughout the experimentation prevented this from occurring again. Odor from the reactors generally smelled of fresh cow manure and was not objectionable to the operators. However, members of the dairy family at the study site did comment that they found the odors objectionable, which probably meant that the odors were somewhat different from the characteristic dairy odor. Foaming in reactors at times posed a problem which was solved by the use of bubble cutters fastened to the mixer shaft. At other times there was very little foam. The variation could not be identified with any operating procedure or parameter and remained an enigma. The bacterial population in the thermophilic reactors was examined under a microscope and found to be very undiversified when compared with the bacterial population in the raw manure. The thermophilic bacteria appeared to be practically all small, gram-positive cocci. The raw manure included many rods and many gram-negative and gram-positive cocci forms.

Table 12. CHARACTERISTICS OF CONTINUOUS REACTION PRODUCTS[a]

Week	Reactor	Reaction number	VS/TS	Sol-COD/TS	Sol-BOD/TS	Total COD/TS	Total-BOD/TS
1	1	14	0.826	0.65	0.26	1.52	–
	2	15	0.865	0.67	0.17	1.57	0.28
	3	20	0.857	0.68	0.19	1.48	0.20
2	1	13	0.838	0.35	0.08	1.19	0.09
	2	16	0.798	0.52	0.14	1.62	0.16
	3	19	0.864	0.39	0.09	1.11	0.11
3	1	9	0.845	0.31	0.04	0.84	0.06
	2	3	0.850	0.34	0.05	1.08	0.06
	3	6	0.843	0.43	0.10	0.85	0.10
4	1	10	0.867	0.21	0.04	0.89	0.09
	2	4	0.865	0.26	0.04	0.97	0.05
	3	5	0.882	0.29	0.07	0.98	0.12
5	1	11	0.886	0.23	0.07	0.91	0.12
	2	8	0.867	0.23	0.06	1.54	0.10
	3	1	0.871	0.20	0.05	–	0.11

[a]Values are presented as a ratio without units, e.g., grams/gram.

Table 12. (Continued)

Week	Reactor	Reaction number	VS/TS	Sol-COD/TS	Sol-BOD/TS	Total COD/TS	Total-BOD/TS
6	1	12	0.855	0.15	0.07	1.41	0.12
	2	7	0.856	0.23	0.08	1.74	0.15
	3	2	0.862	0.34	0.07	1.00	0.12
7	1	22	0.882	0.28	0.11	1.08	0.14
	2	17	0.941	0.36	0.07	1.19	0.15
	3	23	0.877	0.37	0.11	0.91	0.12
8	1	21	0.854	0.37	0.07	0.90	0.11
	2	18	0.878	0.32	0.01	1.09	0.02
	3	24	0.852	0.36	0.06	1.30	0.11
9	1	–	0.856	0.15	0.01	0.54	0.01
	2	–	0.875	0.27	0.02	0.94	0.02
	3	–	0.873	0.15	0.02	0.92	0.02
10	1	–	0.883	0.31	0.01	1.08	0.02
	2	–	0.893	0.27	0.02	1.11	0.02
	3	–	0.835	0.21	0.01	0.76	0.01
Average weeks 1-10			0.863	0.33	0.07	1.12	0.10
Raw manure average			0.861	0.22	0.06	0.96	0.105

[a]Values are presented as a ratio without units, e.g., grams/gram.

Table 13. EFFECT OF VARIABLES ON STABILIZATION OF MANURE

Variable	Soluble-COD/TS	Soluble-BOD/TS
Aeration level:		
A_1	0.31	0.063
A_2	0.37	0.098
A_3	0.37	0.095
A_4	0.37	0.093
Feedrate:		
F_1	0.42	0.108
F_2	0.37	0.084
F_3	0.29	0.071
Temperature:		
T_1	0.27	0.062
T_2	0.44	0.113
Average of all reactions during weeks 1 through 8	0.356	0.0875
Raw manure as fed[a]		
Average	0.22	0.062
Standard deviation	0.07	0.023

[a]See Table 3.

Table 14. SUMMARY OF ANALYSIS OF VARIANCE

I. Biological Energy Generation:

Source of variation	Sum of squares	Degrees of freedom	Mean square	F-ratio test[a]	F-ratio test[b]
Aeration	99,500	3	33,200	6.8	7.8
Feedrate	16,900	2	8,500	1.74	2.00
Temperature	14,200	1	14,200	2.91	3.36
Error	82,900	17	4,880		
Total	213,500	23			

II. Stabilization of Manure:

Source of variation	Sum of squares		Degrees of freedom	Mean square		F-ratio test	
	Sol-COD/ TS	Sol-BOD/ TS		Sol-COD/ TS	Sol-BOD/ TS	Sol-COD/ TS	Sol-BOD/ TS
Aeration	0.0146	0.0048	3	0.00487	0.0016	0.39	0.62
Feedrate	0.0702	0.0054	2	0.0351	0.0027	2.78	1.04
Tempera-ture	0.1837	0.0160	1	0.1837	0.0160	14.6	6.15
Error	0.2145	0.0438	17	0.0126	0.0026		
Total	0.4830	0.0700	23				

[a]F-ratio test based on error mean square of 4,880.

[b]F-ratio test based on error mean square of 4,230 derived from replicate analyses during weeks 6, 7, 9 and 10 as shown in Table 8.

MESOPHILIC REACTIONS

Mesophilic reaction conditions remained unchanged throughout the 10 weeks of experimentation. Product from the thermophilic reactors was fed to the mesophilic reactors. The only mixing was that produced by the aerators and that done manually to break up any solids accumulation on a once or twice a day basis. Table 15 gives conditions and some results of the reactions. Airflow rate was adjusted to 0.24-0.35 l/sec for each reactor. However, it became necessary at times to reduce this flow because of foaming problems. The results again show minimal, overall stabilization of the manure. However, significantly reduced values of total-BOD, soluble-COD and soluble-BOD were recorded. This would be expected because there was very little mechanical action occurring in the reactors to help dissolve additional organic material.

FILTRATION EXPERIMENTS

Experiments with the filter leaf testing apparatus were conducted on products from both the thermophilic and mesophilic reactors. Among 56 recorded tests no substantial differences were noted between the filterability of the two products. The addition of lime or alum alone as a filtering aid did not produce as high a filtration rate as did the addition of lime and alum together or the addition of lime, alum and ferric chloride together. With a formation time of one minute, a drying time of two minutes, Eimco filter cloth number PO801HF, and heavy chemical dosages (for example, 15 percent lime, 1 percent alum, and 3 percent ferric chloride on a dry solids basis), it was possible to achieve a filtration rate of approximately 20 kg/m^2-hr. The filtering rate was not maximized as a function of filter aid chemicals, nor was it optimized in terms of costs. The effort to accomplish this was not justified in view of the treatment and process limitations uncovered in thermophilic and mesophilic treatment steps.

Table 15. CONDITIONS AND PRODUCTS OF MESOPHILIC REACTIONS

Reactor:	1	2	3
Hydraulic and solids residence time, days	10	10	5
Average TS in reactor, percent	11.9	6.3	6.6
Volume of reactor contents, liters	95	95	151
Characteristics of reactor products:			
VS/TS	0.857	0.856	0.853
Total–COD/TS	0.90	1.09	1.08
Total–BOD/TS	0.055	0.04	0.04
Soluble–COD/TS	0.29	0.24	0.27
Soluble–BOD/TS	0.035	0.015	0.02
Apparent removals in percent:[a]			
Total–COD		<10	
Total–BOD		45-60	
Soluble–COD		12-27	
Soluble–BOD		50-80	

[a]Removals based on average characteristics of feed to mesophilic reactors from the thermophilic reactors.

SECTION VII

ENGINEERING AND ECONOMIC CONSIDERATIONS

ENGINEERING CONSIDERATIONS

The successful development of a treatment process incorporating aerobic, thermophilic digestion of dairy cattle manure is limited by inherent characteristics of the manure and of the process. Economic considerations provide an additional limitation upon the process.

A large fraction of dairy cattle manure degrades rather slowly under aerobic conditions, and therefore, complete stabilization of the manure requires more time than does stabilization of normal domestic sludges. This has been attributed to the presence of greater quantities of lignins and cellulosic material in cattle manure.

Maximum rates of aerobic biological activity require an abundant supply of oxygen, and in a liquid system, a large excess of air is needed to obtain sufficient quantities of oxygen in solution. The transfer of oxygen is aided by an increase in diffusivity or diffusion coefficient with temperature. On the other hand, thermophilic temperatures and high solids content result in saturation oxygen concentrations reduced from that of pure water at ambient temperatures. As an example of the magnitude of these factors, data[34,35] indicate that the diffusivity of oxygen in an air-water system increases by approximately 18 percent for a temperature rise from 25° C to 60° C while the solubility of oxygen in pure water decreases by approximately 30 percent for the same temperature rise. The effect of high manure solids concentration is not precisely known but it substantially reduces both the diffusivity and the solubility of oxygen.[36] It is apparent that the net effect of these factors is a substantial reduction in ability to transfer oxygen to solution under thermophilic digestion conditions when compared, for example, with an activated sludge process. This is an unfortunate situation because less oxygen can be supplied precisely when greater biological activity that is potentially available at higher substrate concentrations and temperatures requires more oxygen.

A large excess supply of air could provide the necessary oxygen but this imposes an additional stress upon the process in terms of removing heat from the thermophilic reactor. This heat loss severely limits the maximum temperature that the reactor can reach without a separate external source of heat, which is a relatively costly operating item. The major heat loss with the airstream is latent heat of vaporization of water vapor that saturates the exit airstream. The quantity of water vapor and, therefore, the heat loss increase exponentially with temperature. (The sensible heat required to raise the airstream from ambient temperature to reactor temperature is a relatively minor loss by comparison.) The need to minimize heat losses precludes the use of large quantities of air at thermophilic temperature conditions.

Antithetical requirements for quantity of air supply, as indicated in the above discussion, could not be adequately compromised within limitations of the experimental apparatus used in the current study. Improved conditions were recorded with an oxygen-enriched airstream, and this supports the suitability of a pure oxygen system. A pure oxygen system, particularly under pressure, would substantially increase transfer rates of oxygen and eliminate a major heat loss item.

Other pertinent observations affecting design of a large scale process were foaming and coating of equipment with solids. The foaming problem was not consistent in the experiments, and variations could not be identified with observed parameters. Bubble cutters kept the problem under control and appeared to be a practical solution. The severe clogging of air diffusers on the liquid side experienced in the study indicates unsuitability of small-opening air diffusers for service in this particular type operation. Mechanical aerators would appear to be more suitable toward overcoming the clogging problems.

In summary, indications from the current study are that a technically feasible process would include a pure oxygen system, mechanical aeration which insures plenty of mixing, and foam-control equipment such as mechanical bubble cutters. Elements of this visualized system exist on a commercial scale. In particular, the Union Carbide Corporation, Linde Division has developed the Unox-System for pure oxygen considerably beyond what was examined within the current study. The De Laval Separator Company has developed liquid composting equipment specifically for animal wastes based upon experimental and pilot work. It is the authors' understanding that the proprietary De Laval equipment is currently undergoing performance testing for treatment of dairy manure. Other experiences may exist and a reasonable approach in future work on liquid composting would be to incorporate into the work the background of all relevant experiences with due allowance for the proprietary nature of much previous work.

It was apparent during the current study that substantial, temperature control provisions would be necessary for thermophilic units if air were the oxygen source. With pure oxygen instead of air as the oxygen source, control is less critical because the rate of heat loss and, thereby, the potential for cooling in case of upset is less. Observations during experiments suggested that a separate heating system was unnecessary when heat losses were not excessive and that sufficient temperature control could be provided by varying energy input through mixing.

ECONOMIC CONSIDERATIONS

The economics of dairy operation and the cost of alternative treatment processes are vital to the economic evaluation of a liquid, aerobic composting process. At the present time (end of 1973), a dairy in the Chino-Corona area has capital investment estimated at approximately $1,100 per cow. The estimated gross revenue after recent milk price increases is approximately $1,100 to $1,200 per cow per year. A profit of 10 percent on capital investment corresponds to a net revenue of approximately $110 per cow per year, and for a 500 cow dairy, the total profit would be approximately $55,000. These estimates, especially those pertaining to profits, may be high or low for a specific dairy but are reasonable guides to judge economic consequences of waste treatment costs.

Cost estimates for a thermophilic-mesophilic treatment process, for a 500 cow operation, including vacuum filtration, are summarized in Table 16. The figures are engineering judgments of costs for a treatment process with capacities for 5-day and 10-day hydraulic residence times, respectively, for thermophilic and mesophilic units. The figures do not include waste collection prior to treatment or product handling after treatment. This data indicates a treatment cost of $230 per cow per year which is approximately 20 percent of gross revenue per cow per year and a factor of two greater than estimated profit per cow per year. This cost appears to be a substantially greater burden than can be absorbed within the dairy expenses.

An alternate treatment method which has been demonstrated successfully in the Chino-Corona area is conventional composting. The fact that evaporation substantially exceeds precipitation in this area makes this method particularly attractive because moisture content of manure can be easily reduced to optimum levels of approximately 50 percent moisture. The cost of conventional composting is approximately two dollars per cow per year. The obvious items of cost advantage over liquid composting can be identified with natural drying in place of filtration and predominantly natural aeration in place of mechanical aeration.

Table 16. SUMMARY OF COST ESTIMATES FOR 500 COW TREATMENT PROCESS

	Yearly cost
[a] Thermophilic-mesophilic treatment:	
Capital	$ 22,000
Operation and maintenance	45,000
Cost for oxygen and storage	26,000
Vacuum filtration:	
Capital	11,000
Operation and maintenance	12,000
Total annual cost	$116,000
Annual cost per cow	$ 230

Transportation costs of getting compost to market are a substantial hurdle because the fertilizer value of compost is insufficient to cover transportation costs to potential market areas outside the Santa Ana River basin. The cost of trucking compost to many of the hay fields is estimated to be $20 per cow per year. Dairymen have yet to implement a composting and trucking program which would cost them as much as $20 to $30 per cow per year. This fact substantiates the conclusion that the estimated cost of $230 per cow per year for liquid composting is much too high to be considered economically viable.

SECTION VIII
REFERENCES

1. Santa Ana Watershed Planning Agency, Livestock Waste Study Task Order, No. VI-3, April 1970, 30 p.

2. Adriano, D.C., Pratt, P.F., and Bishop, S.E., "Fate of Inorganic Forms of N and Salt from Land-Disposed Manures from Dairies," Livestock Waste Management and Pollution Abatement, Proceedings International Symposium on Livestock Wastes, Ohio State University, April 19-22, 1971, pp 243-246.

3. Adriano, D.C., Pratt, P.F., and Bishop, S., "Nitrate and Salt in Soils and Ground Waters from Land Disposal of Dairy Manure," Soil Sci. Soc. Amer. Proc. 35, 1971, pp 759-762.

4. Miner, J.R., Bundy, D., and Christenbury, G., Bibliography of Livestock Waste Management, Grant No. 13040 FUU, EPA-R2-72-101, Office of Research and Monitoring of USEPA, December 1972, 137 p.

5. Miner, J.R., and Willrich, T.L., "Livestock Operations and Field-Spread Manure as Sources of Pollutants," Agricultural Practices and Water Quality, Iowa State University, 1970, 231 p.

6. Smith, S.M., and Miner, J.R., "Stream Pollution from Feedlot Runoff," Transactions, 14th Annual Conference on Sanitary Engineering, University of Kansas, 1964, pp. 18-25.

7. Viets, F.G. Jr., "Cattle Feedlot Pollution," Animal Waste Management, Proceedings of National Symposium on Animal Waste Management, Warrenton, VA, September 28-30, 1971, pp 97-105.

8. Madden, J.M., and Dornbush, J.N., "Measurement of Runoff and Runoff Carried Waste from Commercial Feedlots," Livestock Waste Management and Pollution Abatement, Proceedings International Symposium on Livestock Wastes, Ohio State University, April 19-22, 1971, pp 44-47.

9. Edwards, W.M., Chichester, F.W., and Harrold, L.L., "Management of Barnlot Runoff to Improve Downstream Water Quality," Livestock Waste Management and Pollution Abatement, Proceedings International Symposium on Livestock Wastes, Ohio State University, April 19-22, pp 48-50.

10. McCalla, T.M., Ellis, J.R., and Gilbertson, C.B., "Chemical Studies of Solids, Runoff, Soil Profile and Groundwater from Beef Cattle Feedlots at Mead, Nebraska," Waste Management Research, Proceedings of the 1972 Cornell Agricultural Waste Management Conference, pp 211-223.

11. White, R.K., and Edwards, W.M., "Beef Barnlot Runoff and Stream Water Quality," Waste Management Research, Proceedings of the 1972 Cornell Agricultural Waste Management Conference, pp 225-235.

12. Air Quality Criteria for Particulate Matter, U.S. Dept. HEW, PHS, NAPCA Publication No. AP-49, January 1969, 211 p.

13. Senn, C.L., et al., Dairy Waste Management Study, Final Report of PHS Grants 1-D01-VI00137-1 and 2-D01-VI00137-02, Office of Solid Waste Management of EPA, December 1971, 153 p.

14. Sullivan, R.J., Preliminary Air Pollution Survey of Odorous Compounds, U.S. Dept. HEW, PHS, NAPCA Publication No. APTD 69-42, October 1969, 244 p.

15. Loehr, R.C., Pollution Implications of Animal Wastes - A Forward Oriented Review, U.S. Dept. of the Interior, FWPCA, Robert S. Kerr Water Research Center, Ada, Oklahoma, July 1968, pp 39-43.

16. Andrews, J.F., and Kambhu, K., Thermophilic Aerobic Digestion of Organic Solid Wastes, USDHEW, PHS, Office of Solid Wastes Research Grant UI 00550, Final Progress Report, Clemson University, May 1971, 76 p.

17. Kambhu, K., and Andrews, J.F., "Aerobic Thermophilic Process for the Biological Treatment of Wastes - Simulation Studies," Journal WPCF, 41 (5): R 127-R141, May 1969.

18. Shell, G.L., and Boyd, J.L., Composting Dewatered Sewage Sludge, USDHEW, PHS, Bureau of Solid Waste Management Contract No. Ph86-67-103, PHS Publication No. 1936, 1969, 28 p.

19. McGhee, T.J., Torrens, R.L., and Smaus, R.J., "BOD Determinations on Feedlot Runoff," Water and Sewage Works, 119:58-61, June 1972.

20. California Regional Water Quality Control Board - Santa Ana Region, Water Quality Control Plan (Interim), Santa Ana River-Basin 8, June 1971 (Revised April 1973).

21. Santa Ana Watershed Planning Agency, Preliminary Draft of SAWPA Final Report to EPA, published in several parts, 1971-1973.

22. Dale, A.C., and Day, D.L., "Some Aerobic Decomposition Properties of Dairy-Cattle Manure," Trans. A.S.A.E., 10:546-548, 1967.

23. Taiganides, E.P., and Hazen, T.E., "Properties of Farm Animal Excreta," Trans. A.S.A.E., 9:374-376, 1966.

24. Fogg, C.E., "Livestock Waste Management and the Conservation Plan," Livestock Waste Management and Pollution Abatement, Proceedings International Symposium on Livestock Wastes, Ohio State University, April 19-22, 1971, pp 34-35.

25. Hart, S.A., and Turner, M.E., "Lagoons for Livestock Manure," Journal WPCF, 37: 1578-1596, November, 1965.

26. Hart, S.A., "The Management of Livestock Manure," Trans. A.S.A.E., 3:78-80, 1960.

27. Jones, D.D., Day, D.L., and Dale, A.C., "Aerobic Treatment of Livestock Wastes," Univ. of Illinois Agr. Exp. Sta., Bull. 737, May 1970, 55 p.

28. Jones, D.D., Converse, J.C., and Day, D.L., "Aerobic Digestion of Cattle Wastes," Trans. A.S.A.E., 11:757-761, 1968.

29. Peterson, J.R., McCalla, T.M., and Smith, G.E., "Human and Animal Wastes as Fertilizers," Fertilizer Technology and Use, 2nd Edition, Soil Science Society of America, Madison, Wisc., 1971, pp 557-596.

30. Witzell, S.A., McCoy, E., Polkowski, L.B., Attoe, O.J., and Nichols, M.S., "Physical, Chemical and Bacteriological Properties of Bovine Animals," Proceedings of National Symposium on Animal Waste Management, A.S.A.E. Pub. SP-0366, 1966, pp 10-14.

31. Bhagat, S.K., and Proctor, D.E., "Treatment of Dairy Manure by Lagooning," Journal WPCF, 41:785-795, May 1969.

32. Murphy, L.S., Wallingford, G.W., Powers, W.L., and Manges, H.L., "Effects of Solid Beef Feedlot Wastes on Soil Conditions and Plant Growth," Waste Management Research, Proceedings of the 1972 Cornell Agricultural Waste Management Conference, pp 449-464.

33. Hurwitz, E., and Dundas, W.A., "Wet Oxidation of Sewage Sludge," Journal WPCF, 32:918-929, September 1960.

34. Perry, J.H., ed., Perry's Chemical Engineers' Handbook, 4th Edition, New York, McGraw-Hill Book Company, 1963, pp 14-20.

35. Treybal, R.E., Mass Transfer Operations, 2nd Edition, New York, McGraw-Hill Book Company, 1968, p 25.

36. Metcalf and Eddy, Inc., Wastewater Engineering, New York, McGraw-Hill Book Company, 1972, p 346.

SECTION IX
APPENDIX

AERATION EQUIPMENT OBSERVATIONS

1. Types of aeration equipment used during the experiment.

   A. Chromoglass Air Diffusers

      1. Standard (Round Stone), 5 cm x 30 cm (2" x 12")

      2. Standard (Round Stone), 9 cm x 30 cm (3.5" x 12")

   B. PVC piping, 1.3 cm and 1.9 cm (1/2" and 3/4")

      1. 1.3 cm PVC-T-shaped, 15 cm x 15 cm (6" x 6") with 10 holes, 0.16 cm (1/16") in diameter.

      2. 1.3 cm PVC-circular shaped, 20 cm (8") diameter with 15 holes, 0.16 cm in diameter.

      3. 1.9 cm PVC-rectangular sawtooth pattern with 25 holes, 0.16 cm in diameter.

      4. 1.3 cm PVC-straight piece, 15 cm in length with 4 holes, 0.24 cm (3/32") in diameter; 6 holes, 0.24 cm in diameter; one hole 0.95 cm (3/8") in diameter.

2. Observations with each of the above types.

   A. Chromoglass Standard, 5 cm x 30 cm: These diffusers were principally used in the thermophilic reactors, although one was used in a mesophilic reactor. After three weeks of continuous running, clogging of small pores caused air to be diffused only at one end or the other. With air diffusion in a local area of the reactor the mixing system was unable to disperse the air throughout the reactor, and therefore, biological activity was diminished. Also when clogging occurred air rates as high as 0.35 l/sec (0.75 cfm) could not be attained. In addition to the problem of pore clogging, agglomerations of dried material would build up all along the diffusers causing restrictions of airflow. Scraping clean this build-up would alleviate this problem. Higher air rates would cause a greater build-up, amounting to as much as 5 cm (2") in one week's time. After five weeks of continuous operation, airflows could not be maintained. A cleaning solution of dichromate-sulfuric acid was used in an attempt to restore these diffusers to their original operation capabilities. After submerging the diffusers in the cleaning solution for 2 days or more, only one was satisfactorily cleaned.

      In clear water, these air diffusers gave a very fine bubble pattern with excellent air diffusion. But in the reactors with 12% solids, this very fine bubble pattern was not attained. Air tended to surface in large "blurps" and not always along the full length of the diffuser.

All in all, this air diffuser appeared to operate better at low air rates, low solids concentration and with rapid mixing.

B. Chromoglass Standard, 9 cm x 30 cm: These were primarily used in the mesophilic reactors, where greater airflows were desired due to the absence of mixing. The bubble size and pattern in water from these diffusers were larger than those of the 5 cm x 30 cm diffusers. These larger diffusers were more suitable for higher air rates, although they also created large "blurps" rather than small bubbles. In mesophilic reactors with 6% solids, settling occurred after 8 hours even with the higher air rate of 0.35 l/sec. Any difference in settling between 0.12 l/sec and 0.35 l/sec airflow rates was not apparent.

In the thermophilic reactors, the 9 cm x 30 cm diffusers gave greater movement to the contents than did the 5 cm x 30 cm diffuser when mixing action was held constant.

The problems with the 9 cm x 30 cm diffusers were the same as with the 5 cm x 30 cm diffusers in that the pores clogged after periods of one month or more. Generally they passed 0.35 l/sec without difficulty but air diffused out of only a portion of the diffuser. In all cases agglomerations were very hard, dry, and porous.

C. PVC-T-shaped: This shape was experimented with in thermophilic reactor 3, with stirring at 40 rpm (Dayton 1/2 hp Gearmotor), turning three 23 cm x 8 cm (9" x 3") flat blade props, each with ten 0.16 cm (1/16") holes. The purpose of this configuration was to obtain maximum air dispersion directly under the stirring mechanism and have the blades move the air to the outside of the reactor. A folding effect was produced. Initially oxygen uptake increased slightly and the bubble pattern on the top of the reactor appeared much improved in that smaller bubbles were popping all over the surface of the reactor. However, no substantial improvement in treatment or oxygen uptake occurred. Agglomerations did not occur. This aerator was used for about 10 days while a Chromoglass diffuser was being cleaned.

D. PVC-circular shaped: This was used in a thermophilic reactor for 2 weeks, with a propeller made of six 10 cm bolts spaced up and down the stirring shaft from about 8 cm from the surface of the liquid to about 15 cm from the bottom. This combination of aeration and stirring appeared to perform better than most schemes in terms of oxygen uptake. These props turned at about 250 rpm with a mixer speed set at 4. Airflow restriction due to clogging of holes was minimal and there was little agglomeration build-up.

E. PVC-rectangular sawtooth: This was the only aerator used in mesophilic reactor 3A. This aerator fits flat on the bottom of the reactor with holes drilled uniformly along the side of the PVC. Aeration appeared to be even throughout, though solids settled on the bottom. The solids were easily stirred up twice a day. There was a consistent accumulation of bubbles of 40 cm and more in height on the top of the liquid surface. Airflow was held at 0.24 l/sec throughout the experiment. There were no problems with restricted flow and no agglomeration was observed.

F. PVC-straight piece: After replacing a particularly clogged chromoglass diffuser with this diffuser, there was a noticeable increase in oxygen uptake similar to that described in C. above. The problem with this aerator was restrictions in the small holes. Whenever 2 or more holes became clogged, desired quantities of air could not be maintained.

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